Universidad de Oviedo

Holistic Methodology Toward Decarbonizing Built Environment in Hot Climatic Regions

Metodología Holística Hacia la Descarbonización del Entorno Construido en Regiones Climáticas Cálidas

By

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RESUMEN (en español)

En la última década, la tendencia “eco-friendly” a nivel mundial ha resaltado que para lograr edificios de consumo de energía neta cero, es necesario mejorar la eficiencia energética y reducir la huella de carbono en ese sector. En los países en vías de desarrollo, las prácticas de construcción carecen de soluciones sostenibles para lograr este objetivo. Por ello, los responsables políticos deberían diseñar nuevas regulaciones que contemplen soluciones constructivas eficientes energéticamente, aplicables a nuevos edificios y a la rehabilitación de los existentes. Dado que estas soluciones todavía están en fase de investigación, es necesario analizarlas a fondo antes de su ejecución, priorizando la conservación de los recursos sin influir negativamente en el confort y la calidad ambiental interior.

El objetivo principal de esta tesis consiste en un análisis del comportamiento energético y la calidad del aire interior en edificios institucionales en Egipto, para posteriormente, integrarlo en metodologías que podrían contribuir al desarrollo de futuras estrategias de construcción sostenible egipcias. Como punto de partida se utilizó uno de estos edificios educacionales del cual se disponían datos reales de la envolvente térmica, las instalaciones de climatización, la ocupación, el uso y las medidas experimentales. El modelado del edificio de referencia se hizo con el programa de simulación dinámica DesignBuillder, validado con medidas experimentales del consumo de energía. Con este modelo validado, se analizó el comportamiento energético del edificio, así como una serie de mejoras de eficiencia energética y el confort térmico interior, en tres regiones cálidas de Egipto (referencia ASHRAE): Aswan, El Cairo y Alejandría.

La influencia de los parámetros del edificio se evaluó mediante un análisis de sensibilidad local, por su facilidad de implementación en una matriz de decisión, su bajo coste computacional y su sencillez en la representación de resultados. Este estudio incluye la envolvente, la iluminación, las cargas de sistemas y ocupantes y los sistemas de acondicionamiento HVAC. Como resultado se identificó a la climatización como el mayor demandante de energía producido por la ganancia de calor de la envolvente en condiciones de verano.

Como criterios de evaluación se han considerado variables técnicas, ecológicas, económicas y de confort térmico. Estas variables han sido ponderadas para crear una matriz multiobjetivo que permite identificar soluciones que faciliten la toma de decisiones. Se ha probado la aplicabilidad de numerosas soluciones de la envolvente del edificio, en concreto aislamientos térmicos, así como la integración de energías renovables, en particular fotovoltaica integrada en el edificio (BIPV), priorizando las condiciones de confort térmico a través de las horas de incomodidad.

También se ha tenido en cuenta la propagación del COVID-19 en zonas cerradas, considerando posibles soluciones de los sistemas de climatización que permitan controlar y prevenir futuras infecciones, así como algunos mecanismos que contribuyan a reducir el riesgo de infección transmitidas por el aire y lograr futuros edificios a prueba de pandemias.

Una vez optimizado el modelo se aplica a las tres regiones climáticas consideradas, obteniendo resultados muy prometedores en la mejora de la eficiencia energética y en la reducción de emisiones, aproximadamente 41,5%, 40% y 37%, respectivamente, mejorando las condiciones de confort interior en 43%, 42,5% y 37,5%.

En resumen, esta investigación arroja nuevos conocimientos y un profundo análisis sobre el desempeño energético de los edificios institucionales en las tres regiones climáticas cálidas de Egipto evaluadas. Para ello se ha desarrollado una metodología de simulación que incorpora múltiples enfoques en la toma de decisiones, considerando al mismo tiempo evaluaciones ambientales y económicas así como la garantía de mejores niveles de confort térmico.

RESUMEN (en Inglés)

Over the past decade, the global eco-friendly trend has emphasized that to reach net-zero energy consumption buildings, it is necessary to improve energy efficiency and reduce the carbon footprint in the sector. In developing nations, construction practices lack sustainable solutions to achieve this goal. Hence, policymakers should desing new regulations in which "energy-efficient solutions" are contemplated, applicable to new buildings and the rehabilitation of the existing ones. Since these solutions are still in the research phase, it is necessary to evaluate them thoroughly before being implemented, prioritizing the conservation of resources without negatively influencing comfort and indoor environmental quality.

The foundational goal of this dissertation consist of an analysis of the energy performance and indoor air quality in institutional buildings in Egypt, to subsequently integrate this knowledge into methodologies that could feed future Egyptian sustainability contruction strategies. As a starting point, one of these educational buildings was used, from which real data was available on the thermal envelope, air conditioning facilities, occupancy, use and also experimental measurements. The baseline model of the building was done with the dynamic simulation program DesignBuilder, validated with the experimental measurements of energy consumption. With this validated model, the energy performance of the building was analyzed, as well as a series of improvements in energy efficiency and indoor thermal comfort, in three hot regions of Egypt (ASHRAE reference): Aswan, Cairo and Alexandria

The influence of the building parameters was assessed through a local sensitivity analysis, due

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to its ease of implementation in a decision matrix, low computation cost, and simplicity in the representation of the outcomes. This study includes building envelope, lighting, plug loads, occupant's loads, and HVAC conditioning systems. As a result, air conditioning was identified as the greatest energy demand produced by the envelope heat gain in summer conditions.

Technical, ecological, economic, and thermal comfort variables have been considered as evaluation criteria. These variables have been weighted to create a multi-objective matrix that enables the identification of solutions that facilitate the decision-making process. The applicability of numerous building envelope solutions has been tested, specifically thermal insulations, as well as the integration of renewable energies, particularly building-integrated photovoltaics (BIPV), prioritizing the resulting thermal comfort conditions through hours of discomfort.

The spread of COVID-19 in enclosed zones has also been taken into account, considering possible solutions for heating, ventilation and air conditioning systems that allow controlling and preventing future infections, as well as some mechanisms that contribute to reducing the risk of airborne infection and making future buildings pandemic-proof.

Once the model has been optimized, it is applied to the three climatic regions considered, obtaining very promising results in the improvement of energy efficiency and the reduction of emissions, approximately 41.5 %, 40% and 37%, respectively, improving interior comfort conditions by 43%, 42.5% and 37.5%.

In summary, this investigation sheds new insights and in-depth analysis on the energy performance of institutional buildings in three studied hot climatic regions of Egypt. For this, a simulation methodology has been developed that incorporates multiple decision-making approaches while also considering enviro-economic evaluations and ensuring enhanced thermal comfort levels.

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PUBLICATIONS

Aside from this dissertation, the research has been published in various journals. These publications represent the primary author's research as well as the co-authors' supervisory.

- **William, M. A**., Suárez-López, M. J., Soutullo, S., Fouad, M. M., & Hanafy, A. A. (2022). Enviro-economic assessment of buildings decarbonization scenarios in hot climates: Mindset toward energy-efficiency. *Energy Reports, CEES 2022* (**Accepted**).

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- **William, M. A**., Suárez-López, M. J., Soutullo, S., & Hanafy, A. A. (2021). Building envelopes toward energy-efficient buildings: A balanced multi-approach decision making. *International Journal of Energy Research*, 45(15), 21096-21113.

- **William, M. A**., Suárez-López, M. J., Soutullo, S., & Hanafy, A. A. (2021). Techno-economic evaluation of building envelope solutions in hot arid climate: A case study of educational building. *Energy Reports*, 7, 550-558.

- **William, M. A**., Elharidi, A. M., Hanafy, A. A., Attia, A., & Elhelw, M. (2020). Energy-efficient retrofitting strategies for healthcare facilities in hot-humid climate: Parametric and economical analysis. *Alexandria Engineering Journal*, 59(6), 4549-4562.

- **William, M**., El-Haridi, A., Hanafy, A., & El-Sayed, A. (2019, November). Assessing the energy efficiency and environmental impact of an Egyptian hospital building. In IOP Conference Series: *Earth and Environmental Science* (Vol. 397, No. 1, p. 012006). IOP Publishing.

- **William, M. A**., El-Haridi, A. M., Hanafy, A. A., & El-Sayed, A. E. H. A. (2019). Assessing the Energy Efficiency improvement for hospitals in Egypt using building simulation modeling. ERJ. *Engineering Research Journal*, 42(1), 21-34.

ABSTRACT

Over the past decade, the global eco-friendly trend has emphasized the need to improve energy efficiency and reduce carbon footprint in the built environment to achieve net-zero energy consumption buildings. In developing nations, building construction practices lack sustainable solutions for attaining zero-energy buildings facilities. Hence, policymakers should design and enact new regulations in which "energy-efficient solutions" are contemplated, applicable both to new constructions and renovations of existing buildings, although these design constructive options should be thoroughly investigated and analyzed prior to execution. Resources conservation without negatively influencing human comfortability is a gigantic dare for all designers. Thus, improving indoor environmental quality (IEQ) may be another critical element in the improvement of energy efficiency.

The foundational goal of this dissertation is to have a deeper understanding of the energy performance and indoor air quality of the existing building, more specifically in institutional buildings located in Egypt, to subsequently integrate this knowledge into methodologies that could feed future Egyptian sustainability construction strategies.

In order to know the current status of Egyptian institutional buildings and their energy performance, one of these buildings was used as a case study. Specifically, an educational building was assessed for which real data were available on the thermal envelope, air conditioning facilities, occupancy, use, and experimental measurements. Through the use of dynamic simulation tools, the baseline model of the educational building was designed and developed with the DesignBuilder program, validated with experimental measurements of energy consumption. With this model, the energy performance of the building was analyzed, as well as the incorporation of a series of solutions that improved energy efficiency and indoor thermal comfort, in three hot regions in Egypt, according to ASHRAE, such as Aswan, Cairo and Alexandria.

The analysis of the influence of the building parameters is carried out through a local sensitivity analysis due to its ease of implementation in a decision matrix, low computation cost, and easy representation of the outcomes. This study includes building envelope,

lighting, plug loads, occupant's loads, and HVAC conditioning systems. This sensitivity analysis of the baseline case revealed that the air conditioning facility is the most energy-demanding component derived from the envelope heat gain in summer conditions.

As evaluation criteria or cost functions, this study addressed technical, ecological, economic, and thermal comfort variables. These variables have been weighted to construct a multi-objective matrix that enables the identification of solutions that facilitate the decision-making process in accordance with the evaluation criteria. Based on this, the applicability of numerous energy-efficient solutions for the building envelope was tested, specifically thermal insulations, as well as the integration of renewable energies, particularly building-integrated photovoltaics (BIPV), prioritizing the resulting thermal comfort conditions represented by discomfort hours (DCHs).

Since the thesis was developed during a global pandemic, the spread of COVID-19 in enclosed zones has been taken into account, considering possible solutions for heating, ventilation and air conditioning systems that allow controlling and preventing future infections, as well as some mechanisms that contribute to reducing the risk of airborne infection and making future buildings pandemic-proof.

Once the model has been optimized, it is applied to the three climatic regions considered (Aswan, Cairo and Alexandria), and very promising results are obtained both in improving energy efficiency and reducing emissions, approximately 41.5 %, 40% and 37%, respectively, improving interior comfort conditions by 43%, 42.5% and 37.5%.

In summary, this investigation sheds new insights and in-depth analysis on the energy performance of institutional buildings in three assessed hot climatic regions of Egypt. For this, a simulation methodology has been developed that incorporates multiple decision-making approaches while also considering enviro-economic evaluations and ensuring enhanced thermal comfort levels.

RESUMEN

En la última década, la tendencia “eco-friendly” a nivel mundial ha resaltado que para lograr edificios de consumo de energía neta cero, es necesario mejorar la eficiencia energética y reducir la huella de carbono en ese sector. En los países en vías de desarrollo, las prácticas de construcción carecen de soluciones sostenibles para lograr este objetivo. Por ello, los responsables políticos deberían diseñar nuevas regulaciones que contemplen soluciones constructivas eficientes energéticamente, aplicables a nuevos edificios y a la rehabilitación de los existentes. Dado que estas soluciones todavía están en fase de investigación, es necesario analizarlas a fondo antes de su ejecución, priorizando la conservación de los recursos sin influir negativamente en el confort y la calidad ambiental interior.

El objetivo principal de esta tesis consiste en un análisis del comportamiento energético y la calidad del aire interior en edificios institucionales en Egipto, para posteriormente, integrarlo en metodologías que podrían contribuir al desarrollo de futuras estrategias de construcción sostenible egipcias. Como punto de partida se utilizó uno de estos edificios educacionales del cual se disponían datos reales de la envolvente térmica, las instalaciones de climatización, la ocupación, el uso y las medidas experimentales. El modelado del edificio de referencia se hizo con el programa de simulación dinámica DesignBuillder, validado con medidas experimentales del consumo de energía. Con este modelo validado, se analizó el comportamiento energético del edificio, así como una serie de mejoras de eficiencia energética y el confort térmico interior, en tres regiones cálidas de Egipto (referencia ASHRAE): Aswan, El Cairo y Alejandría.

La influencia de los parámetros del edificio se evaluó mediante un análisis de sensibilidad local, por su facilidad de implementación en una matriz de decisión, su bajo coste computacional y su sencillez en la representación de resultados. Este estudio incluye la envolvente, la iluminación, las cargas de sistemas y ocupantes y los sistemas de acondicionamiento HVAC. Como resultado se identificó a la climatización como el mayor demandante de energía producido por la ganancia de calor de la envolvente en condiciones de verano.

Como criterios de evaluación se han considerado variables técnicas, ecológicas, económicas y de confort térmico. Estas variables han sido ponderadas para crear una matriz multiobjetivo que permite identificar soluciones que faciliten la toma de decisiones. Se ha probado la aplicabilidad de numerosas soluciones de la envolvente del edificio, en concreto aislamientos térmicos, así como la integración de energías renovables, en particular fotovoltaica integrada en el edificio (BIPV), priorizando las condiciones de confort térmico a través de las horas de incomodidad.

También se ha tenido en cuenta la propagación del COVID-19 en zonas cerradas, considerando posibles soluciones de los sistemas de climatización que permitan controlar y prevenir futuras infecciones, así como algunos mecanismos que contribuyan a reducir el riesgo de infección transmitidas por el aire y lograr futuros edificios a prueba de pandemias.

Una vez optimizado el modelo se aplica a las tres regiones climáticas consideradas, obteniendo resultados muy prometedores en la mejora de la eficiencia energética y en la reducción de emisiones, aproximadamente 41,5%, 40% y 37%, respectivamente, mejorando las condiciones de confort interior en 43%, 42,5% y 37,5%.

En resumen, esta investigación arroja nuevos conocimientos y un profundo análisis sobre el desempeño energético de los edificios institucionales en las tres regiones climáticas cálidas de Egipto evaluadas. Para ello se ha desarrollado una metodología de simulación que incorpora múltiples enfoques en la toma de decisiones, considerando al mismo tiempo evaluaciones ambientales y económicas así como la garantía de mejores niveles de confort térmico.

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ABBREVIATIONS

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulations
BIPV	Building Integrated Photovoltaic
BPA	Building Performance Analysis
BTO	Building Technologies Office
CAV	Constant Air Volume
CO_2	Carbon Dioxide
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DBT	Dry Bulb Temperature
DCH	Discomfort Hours
DOAS	Dedicated Outdoor Air System
DOE	US Department of Energy
EPS	Expanded Polystyrene
EUI	Energy Use Intensity
FCU	Fan Coil Units
GHG	Green House Gases
GIPV	Glazing Integrated Photovoltaic
GW	Glass wool
GWh	Gigawatt Hours
HVAC	Heating, Ventilation, And Air Conditioning
IEQ	Indoor Environmental Quality
Ins	Insulation Material
IoT	Internet of Things
IRR	Internal Rate of Return
kWh	Kilowatt-hours
LPD	Lighting Power Densities
NACA	National Asthma Council Australia
NMBE	Normalized Mean Bias Error
NPV	Net Present Value
NZEB	Net Zero Energy Building

PBP	Payback Period
PPL	Plug and Process Load
PU	Polyurethane
PV	Photovoltaic
RMSE	Root Mean Square Error
ROI	Return On Investment
RP	Reflective Paint
SHGC	Solar Heat Gain Coefficient
U	Overall Heat Transfer Coefficient
VAV	Variable Air Volume
WBT	Wet Bulb Temperature
WWR	Window-Wall Ratio
XPS	Extruded Polystyrene

1. INTRODUCTION

1.1 Background

Climate change mitigation and adaptation are critical concerns of the twenty-first century. It presents significant environmental threats, human life, and the global economy. Some regions worldwide are currently experiencing the consequences of climate change, such as rising sea levels, severe weather, floods, water shortages, and hurricanes. Such changes are occurring due to tremendous quantities of greenhouse gases (GHG) being emitted to the environment as a consequence of human acts occurring on a global scale, most notably fossil fuel combustion for energy generation and mobility. Human activity is the critical driver for greenhouse gas emissions, particularly CO_2, which considerably impact global warming [1–3]. Energy-related CO_2 emissions reached a new historical record in 2018 [4]. The annual rise in global energy-related CO_2 emissions is now on pace to be the second greatest ever [5]. Pursuant to the Energy Information Administration (EIA), primary energy demand has increased by 49% over the past two decades, while CO_2 emissions have increased by 43%, with an estimated yearly increase of 2% and 1.8%, respectively [6]. Between 2000 and 2015, universal energy use resulted in an expansion in carbon emissions by 44% [7]. For more than a century, global temperatures have risen at an ever-increasing rate. They are presently the hottest recorded derived by global warming and the greenhouse effect shown in Figure (1-1).

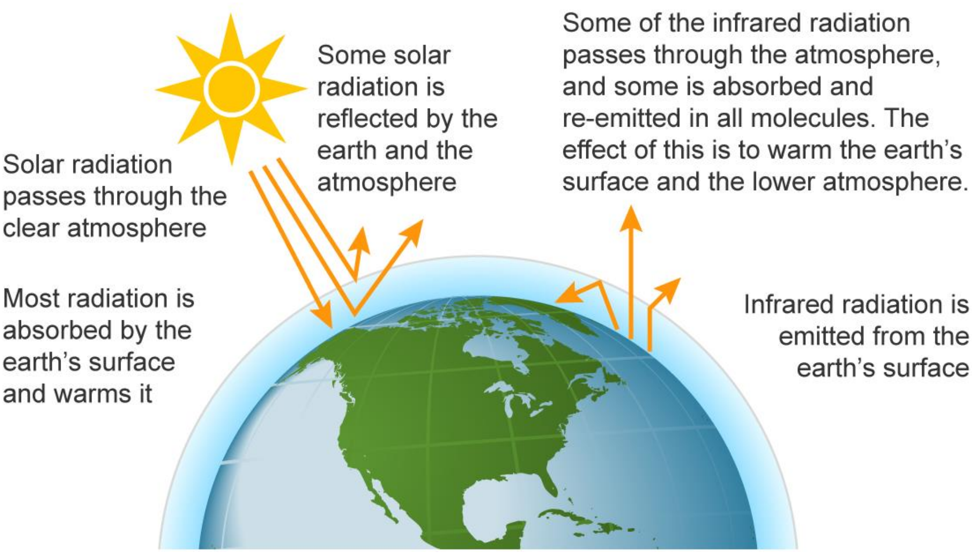

Figure 1-1. The greenhouse effect [8]

Governments have been concerned about the need for energy since the 1970s global energy crisis and the subsequent global warming phenomena, threatening humanity's future. Since the late 1980s and early 1990s, global knowledge of the link between environmental pollution and energy use has pushed energy efficiency to the center of the worldwide agenda. To reduce the use of fuel combustion-derived energy, such as electricity generated in typical fossil power plants and its renewable energies replacements, policymakers are updating their codes and standards globally.

1.2. Energy in Egypt

1.2.1. Current Status

Egypt is Africa's most significant non-OPEC producer of natural gas and oil and the continent's second-largest producer of natural gas. Nevertheless, it is Africa's top user of oil and natural gas. About 95% of Egypt’s overall energy consumption is driven by oil and natural gas, with the remaining being fueled by coal, hydropower, and renewables as Figure (1-2).

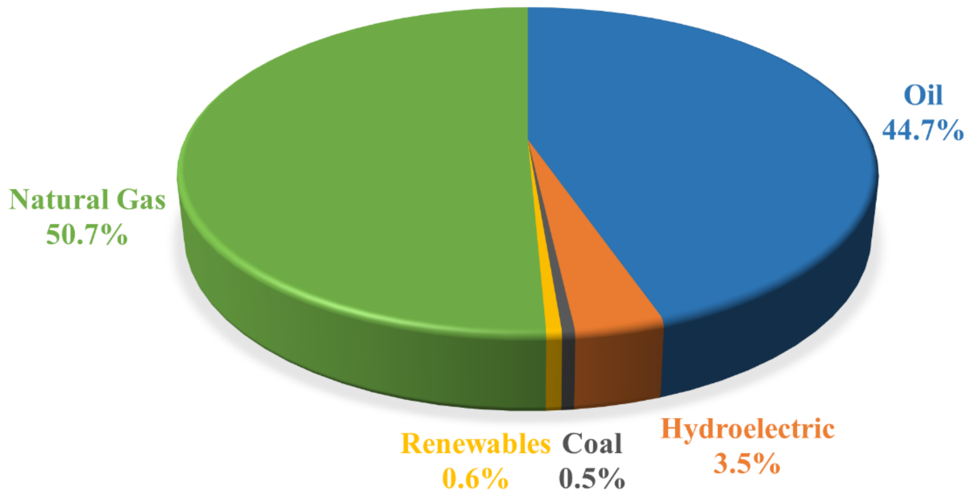

Figure 1-2. Primary energy consumption in Egypt by fuel [9]

As in several other countries, Egyptian energy consumption has risen significantly since the 1990s, increasing the frequency of power outages with significant economic, political, and social consequences. Since 2010, Egypt's electrical consumption has increased by 6-7% annually [10]. The increased urbanization, particularly in the Nile Delta, has been a major source of demand rise [11]. As a result of urban expansion, climate changes, and global temperature increases, larger-sized air-conditioning systems are required to fulfill the new cooling needs in hot weather [12–14].

Because of the rise in domestic consumption, Egypt's energy sector has increased its electrical generating capacity. According to the Egyptian official reports, Egypt's installed electrical capacity was 58.353 GW in 2018/2019, with an increase of nearly 6% over the anticipated capacity of 55.213 GW in 2017/2018 [15]. This energy primarily supplies buildings with the electrical energy they need for different purposes. Electricity production that relies on the combustion of petroleum-based fuels emits CO_2 into the atmosphere, resulting in a slew of environmental disasters.

With the ongoing deterioration of conventional fossil resources and rising energy consumption, Egypt's traditional main energy supplies will be insufficient to supply needs by 2035 [16]. To overcome this scenario, the authorities should implement three strategies: lower demand, enhance the supply and expand Egypt's domestic renewable energy potential in order to diversify its energy mix [16].

1.2.2. Energy in Buildings

The tremendous increase in global energy consumption has sparked widespread worry about supply constraints, resource exhaustion, and severe environmental consequences such as ozone layer degradation, climatic change, and global warming in the past years. Over the next few decades, scientists expect that global temperatures will continue to increase mainly due to human-caused greenhouse gas emissions [17]. Furthermore, they believe that metropolitan areas are anticipated to generate over 80% of GHG by 2050 [18]. Buildings are presently the world's leading energy consumer, representing around one-third of worldwide energy use [19,20]. Buildings utilize almost 30%-40% of universal energy production and are responsible for nearly 19% of GHG emissions [21–23]. While human discomfort in hot regions leads to an increase in air conditioning needs, the need to maintain comfortable indoor temperatures is driving an increase in building energy demand globally. A byproduct, the amount of energy used in those facilities regularly increases because of the increased use of air conditioners. This sector is among the highest growth in the Middle East and North Africa (MENA) nations, with Egypt the most energy-intensive in buildings [24]. In Egypt, buildings exploit about 70% of the total energy [17,25]. This percentage is predicted to increase exponentially due to the expansion of developing new cities and urban communities nowadays in Egypt. Energy savings are more likely to be found in commercial properties since the majority of this energy, around 50%, is being used for space conditioning [22,26–28]. Air-conditioned commercial building designs that retain residents’ high degree of comfortability at the expense of high energy utilization and CO_2 emissions are popular with clients and most designers [24]. Until the Egyptian Commercial Buildings Energy Code was introduced in 2005, no energy performance standards had to be met by urban development in Egypt [24]. Even though there is an outdated energy code, policies do not force implementing its recommended measures. Moreover, considering climate change tendencies, buildings constructed using outdated designs may become energy inefficient like most buildings in Egypt.

1.2.2.1. Energy-Efficiency in Buildings

Realizing that the built environment accounts for a large amount of a country's energy demand, sustainable measures should be intended to limit energy utilization while maintaining comfort conditions and environmental standards. New properties are anticipated to reduce overall energy consumption by 20% to 50% through including effective design solutions for building envelopes, HVAC, lighting, and appliances, among others (e.g., workplace appliances) [22]. Therefore, designers will have to propose new designs for spaces, construction methods, materials, and efficient retrofit procedures in existing facilities. The attainment of energy efficiency is among the most critical design elements; regarding this expectation, various international entities and organizations as the European Union and ASHRAE have increased their efforts to encourage the adoption of energy-efficient buildings initiatives.

Numerous technologies and solutions have been investigated and determined in developed nations, but their practicality and impact in developing countries are rarely thoroughly reviewed [24]. Therefore, the movement toward decarbonization of the built environment has entered a new era, with an increased emphasis on building sciences, control systems, and simulations. Refitting existing buildings or extending energy-efficient solutions into modern designs provides significant opportunities to reduce global energy-related carbon emissions. But, due to the myriad variables that affect a building's energy use, including the building envelope, physical characteristics, installed HVAC systems/equipment, meteorological/climatic parameters, and occupant behavior, assessing a building's energy performance remains a formidable challenge [17]. Energy performance analysis is critical for designing the optimal design and operation of new facilities, as well as for appointing the most efficient retrofits for existing buildings. The majority of building owners in developing nations have been conditioned to believe that energy efficiency must be more expensive, yet well-designed, energy-efficient buildings can be constructed at a lower cost than traditional constructions [22]. Early design phases have a considerable impact on future performance in terms of energy and resource utilization, and this is when the optimization potential may be used most efficiently and at a minimal cost. With this objective in mind, energy models have evolved into a useful tool for completing a variety of high-performance buildings. Engineers and designers frequently utilize dynamic simulations and experimental measurements/data to assess building energy performance in order to achieve specific goals such as decreasing energy consumption and ecological effects while ensuring human comfort [17,22].

1.3. Problem Definition

The Egyptian energy industry is now confronted with a slew of overlapping and conflicting challenges. To achieve long-term stability and social equality, Egypt must focus on ecologically and socially sustainable growth to meet the current needs without jeopardizing the needs of future generations [29]. As a result, unconventional solutions are urgently required to address future energy and pollution issues and the threat of rising electricity costs. Egypt's initial response was to adopt an integrated energy plan aimed at reducing energy demand and providing the secure, dependable, and cheap energy services needed to promote economic stability and progress [24,30]. Energy-efficient buildings are considered one of the optimum solutions to the situation of the energy crisis in Egypt. Therefore, Egypt has recently deepened its efforts to introduce new sustainable building design standards, especially for the new urban communities, enhancing energy use, environmental impact, and indoor environmental quality (IEQ). The research outcomes are to serve as a guide for decision-makers and low-energy buildings certificates in different climatic regions of Egypt.

1.4. Value of Solving the Problem (Motivation)

In order to have a broader insight into how buildings utilize energy and how that affects the economy, ecology, and society at large, it is crucial to focus on energy efficiency and indoor environmental quality (IEQ). Energy efficiency in buildings typically results in reduced energy usage for space heating and cooling, improved comfort, and increased value of the property. In developing nations where electricity is sporadic and power rationing is common, end customers have a substantial demand for fossil fuel-based energy production. Reducing the amount of power and energy needed in a building minimizes capital expenditure and operating costs. Understanding the potential to enhance energy and environmental performances in Egyptian facilities through studying their energy efficiency and IEQ will result in well-grounded decision-making, enhanced occupants' indoor conditions and productivity, as well as economic revenue to building owners.

1.5. Objectives

This dissertation aims to evaluate the energy performance and improvements for air-conditioned institutional buildings in Egypt using building simulation modeling. The research study is motivated by developing comprehensive building energy standards in Egypt. Results presented in this research are ordered similar to how building energy performance study is carried out, and the required information is coming in. It is expected to give helpful information to Egypt's designers, decision-makers, building owners, and policymakers to analyze and achieve energy efficiency in building design and operation.

The objectives of this study are summarized as:

- Study of the art on existing Egyptian institutional facilities' energy utilization and indoor environmental quality (IEQ).
- Methodological development for modeling the energy performance of current Egyptian institutional buildings that may be used in the future to inform improvements and policy directions.
- Employ this modeling methodology to assess the relative and sequential influence of relevant factors and provide this info to decision-makers in a feasible manner.
- Propose enviro-economic buildings decarbonization solutions for Egyptian buildings through multi-approach decision-making.
- Illustrate how the methodology can be utilized in a variety of climatic conditions.
- Demonstrate energy-efficient solutions, enhancing IEQ and reducing airborne transmission risk.

1.6. Scope of Work and Novelty

This dissertation focuses on institutional buildings in Egypt. Institutional building energy performance characteristics in several climate regions are examined using a building energy performance simulation tool. The novelty of this work relies on proposing an energy-efficient methodology integrating various parameters into the decision-making phase. The methodology utilizes local sensitivity analysis and parametric simulations considering several cost functions as energy efficiency, CO_2 emissions, and thermal comfort toward creating a novel balanced decision matrix.

1.7. Organization of the dissertation

This dissertation is organized into five chapters, each dealing with a particular aspect of assessing the energy performance in addition to the references and appendix sections.

Chapter One:	Background on climate change and energy problem, and introduction for Egypt's electric consumption and increased power generation. As a consequence of the increased generation of power, CO_2 emissions increase, negatively affecting the environment.
Chapter Two:	A literature review of previous research and studies on building energy performance establishes the latest finding in the study area and highlights the research gaps.
Chapter Three:	Highlight the theoretical analysis, focusing on buildings simulation tools, economic assessment, methodology, and case study.
Chapter Four:	The result and discussion for the solutions in terms of energy efficiency, CO_2 emissions reduction, thermal comfort assessment, and economic analysis are summarized in this chapter.
Chapter Five:	Summarizes the Conclusions, Recommendations, and Future Work
Chapter Six:	Conclusiones Y Recomendaciones Para Futuros Trabajos
References	This chapter gathers the references cited in this work
Appendix	This section gathers the published manuscript for the dissertation

2. LITERATURE REVIEW

Building energy performance has a significant difficulty if it fulfills the increased demand for energy while also increasing occupants' comfort. This challenge is quite relevant in countries like Egypt, where new energy standards for buildings are being developed, taking into account the country's contextual factors: hot climates, inefficient existing buildings, strong dependence on fossil fuels, and high cooling demands. In this context, this chapter's main goal is to identify the most relevant published discoveries in the fields of building energy performance, renewable integration, thermal comfort, and the use of dynamic simulation tools to increase energy efficiency and reduce pollutant emissions in buildings. Based on the analysis of Egypt's building energy problem, this chapter focuses on building energy management, air-conditioning systems, building envelope highlighting thermal insulation and the integration of photovoltaic devices, and lastly, the optimal and healthy use of HVAC systems. Finally, a conclusion is provided summarizing and identifying the research gap.

2.1 Building Energy Management and Saving

Designing and constructing efficient buildings is based on two principles: minimizing the needs for energy use through energy efficiency strategies and supplying the remaining needs with renewable and low-carbon technologies. Energy efficiency and conservation are critical for long-term sustainable growth. Therefore, energy management refers to the practice of developing energy conservation procedures, analyzing energy usage, and monitoring energy in buildings. The optimization of the global process requires adequate comprehensive management of all building flows and parameters. In this context, several studies have addressed this issue.

Mynhardt [31] evaluates the annual energy performance of a new educational facility at the University of Stellenbosch in Stellenbosch, South Africa, employing both the South African Green Star grading system and national energy-efficiency building codes. For modeling the energy performance of the building, a quantitative physical modeling method was employed with EnergyPlus as the energy and thermal load simulation engine. It was discovered as a result that the actual building consumes 16.5% more energy yearly than the notional building. Because the Green Star South Africa (GSSA) energy conditional criteria are not met, a Green Star rating is not achievable based on the initial design stage data. The HVAC system and lighting are the key culprits in the substantial discrepancy in energy consumption. The notional building's HVAC system was determined to be more efficient than the fan-coil system employed in the existing building, even though the notional building had a lighting power density that was 62.9% higher. To evaluate potential savings, an investigation of the actual building fabric and the HVAC and lighting systems was performed. In conclusion, the author remarked that a reduction in lighting density and a more efficient HVAC solution would have a considerable impact on the overall energy consumption of the property, resulting in a reduction in the building's ecological footprint. The author additionally performed a brief financial assessment on these substantial energy improvement potentials to highlight that the investment is beneficial.

Iwayemi et al. [32] stated that commercial and residential buildings are the most consumers of electricity, being the primary contributors to global warming. As a result, building energy management (BEM) solutions are designed to manage energy use and the cost of energy expenses while also increasing occupants' thermal comfort and productivity. Non-intrusive equipment loads monitoring and smart lighting provide the highest reductions in domestic and commercial building energy use.

Attia et al. [33] attempt to develop simulated representative building energy data sets and benchmark models for Egypt's residential sector. The findings of a recent field investigation conducted in Egypt on residential apartment buildings were reported. EnergyPlus was utilized to simulate the surveyed data using two building simulation models. The study indicated that the simulation models should be verified against the apartment characteristics. Two building performance simulation models were developed in Alexandria, Cairo, and Asyut, Egypt, to reflect the average energy consumption characteristics of air conditioning in residential units. With regards to building architecture and construction, the study established two extensive models to describe the energy use profiles for lighting, air conditioning units, domestic hot water, and appliances, with the aim of assessing the cost and energy implications of Egypt's new energy standard in the future.

Vakiloroaya et al. [34] used the model-based gradient projection optimization method to analyze the energy-saving challenge for air-cooled central cooling plant systems. Theoretical and empirical system models incorporate mechanical relationships between components for the system's operating variables. A wide variety of experimentally acquired data from the chiller in operation was used to validate the integrated simulation tool. The simulation results demonstrate the potential for significant energy savings and comfort enhancements with the recommended technique.

Chuah [35] declared that energy is amongst the most significant resources necessary for modern human civilization. Globally, energy consumption is anticipated to significantly rise by more than 50% by 2035, compared to present levels. The study outlines strategies for analyzing and optimizing energy use in buildings using:

1- Sustainable energy generation through photovoltaics and wind turbines, as a means of lowering energy costs.
2- An occupant-level sensing (OLS) system is capable of providing information about the exact environmental conditions encountered by each building occupier.
3- Efficient localized cooling and heating systems and occupant-level indoor air quality control and smart lighting.

Ahn et al. [36] investigated the influence of lighting on cooling and heating demands. LED has the potential to provide energy savings. They claimed that various countries have policies to promote its use due to its remarkable efficiency and longer lifespan compared to other lighting fixtures. EnergyPlus simulation tool was utilized to simulate the energy consumption of various light fixtures of the Green Building in Daejeon, Korea, and a virtual building provided by the U.S. Department of Energy. Comparing the general fluorescent lighting and LED, the controlling strategy is more applicable to LED than fluorescent. For cooling purposes, the adoption of LED lighting in conjunction with this control approach can help improve energy efficiency.

Carbonaria et al. [37] evaluated hospitals and community centers' energy usage and ecological impact. The paper outlined that this is primarily due to the buildings' age, low energy efficiency, and lack of a basic maintenance plan. The current article analyses three acute healthcare facilities and two community clinics in Italy prior to EPC development in order to determine the economic feasibility of retrofit solutions. Energy audits results carried out in 2014, the analyses of consumption measured over the last three years, and the user profiles assessment were all considered for the development of models to break down the overall consumption and assess potential savings. Improvement solutions include improved building envelope insulation, electromechanical and lighting equipment enhancement, the introduction of renewable energy, and better system management. Finally, payback durations for the most likely scenarios were calculated.

Ghahramani et al. [38] utilized EnergyPlus to provide an approach for quantifying the influence of building construction, climate, occupancy schedule, and setpoints on HVAC energy consumption in office buildings compared to DOE reference office models. The researchers claimed that annual ideal setpoint in the range of 22.5 ± 1 °C, 22.5 ± 2 °C, and 22.5 ± 3 °C would result in average reductions of 7.5%, 12.7%, and 16.4%, respectively, as compared to the baseline set point of 22.5 °C. The findings disclosed in this research can assist building stakeholders in better understanding the approximate potential savings from energy-aware HVAC system control parameter selection and assist building stakeholders in making decisions on energy-saving measures.

Hoyt et al. [39] investigated the influence of parametrical change in heating and cooling setpoints in seven ASHRAE climate regions and six separate medium-sized office buildings, each representing a building control retrofitting or a newly developed building through a simulation study. Without sacrificing comfort, increasing the cooling setpoint from 22.2 to 25 °C yields an average of 29% of cooling energy and 27% of overall HVAC consumption. Depending on the climate, additional temperature bands produced through fans or human controls can result in HVAC savings of between 32% and 73%. Additionally, the authors said that reducing VAV minimum flow fractions will significantly influence HVAC energy usage, resulting in an average savings of 31%. They concluded that energy reduction through cooling and fans varied from 15% to 38%.

Miyaoka et al. [40] investigated the effect of LED bulbs on air conditioning and energy consumption in commercial buildings. The authors asserted that the air conditioning demand induced by lights is linked to the lamp's electrical consumption. As a result, replacing traditional fluorescents with LEDs will decrease air conditioning energy use. Based on the thermal properties of fluorescent and LED lighting, the authors evaluated the air-conditioning demand and consumption in an electronics store in central Japan over a year. Their research reduced the annual cooling load by 17% by replacing fluorescent bulbs with LEDs. As a result, the annual electricity required by lights and air conditioning was reduced by 21%.

Elharidi et al. [41] claim that natural ventilation and localized cooling systems controlled by individuals in Egyptian offices have a power consumption of less than half that of centrally serviced buildings. Additionally, the authors highlighted that some aspects that contributed to a potential 30% savings were occupant behavior (e.g., use of systems and temperatures) and the efficiency of various systems, including HVAC, lighting, and appliances. Finally, policy efforts were proposed to encourage energy-efficient systems and energy-conscious behavior that could lower the energy consumption of typical offices by 50%.

Dutta et al. [42] investigated different glazing to reduce the cooling loads of buildings in tropical environments. Five alternative single- and double-glazing glass types, each with a different energy savings potential, are studied using two simulation models. Five alternative types of commercially available window glasses were modeled using TRNSYS and eQuest simulation tools, validated with lab-tested results. According to the findings, Solar Heat Gain Coefficient (SHGC) is a more critical element in glazing than U-value in reducing building energy cooling load.

Fathalian et al. [43] mentioned that a proper decision about the impact of different energy-efficient strategies could not be easily studied without energy simulation tools. In this study, the authors used DesignBuilder software for the annual energy consumption of an office building in Iran. They validated the simulation results by the monthly energy consumption of the building with an error of 1.6%. They proposed three strategies for energy management consumption, starting by replacing single glazing windows with double Low-E glazing windows. Then they studied installing a thermal insulation sheet on the external wall of the building, use of horizontal shadings on the outside, and removal of the internal shades. The results showed that these strategies lead to 14%, 18%, and 13% energy consumption reduction.

Ghose et al. [44] studied the ecological consequences of New Zealand's refurbished buildings in their research. According to their findings, authors recommend that large facilities prioritize efficient HVAC systems and lower WWR (window-wall ratio) ratios, while small buildings should target materials with less embodied effects on the environment. Finally, all facilities were expected to have completed profound energy retrofitting processes, resulting in an operating energy consumption reduction of at least 60%.

Emil and Diab [45] postulate that buildings account for around 66–74% of Egypt's energy consumption. They examined the consequences of implementing energy efficiency measures on an educational facility in Cairo using EnergyPlus toward an optimal energy requirement. They concluded that the walls, roof, and windows retrofit led to a considerable energy reduction of about 29%. In addition, annual energy savings of over 50% were achieved by upgrading the HVAC mechanical systems.

2.2 Right-sizing of Air Conditioning Systems

For optimal energy efficiency and comfort, cooling system size is particularly important in hot locations such as Egypt, according to the **US National Renewable Energy Laboratory (NREL)** [46]. Oversized equipment has a higher initial cost, lower efficiency, higher energy expenses, and the potential to compromise comfort. Proper equipment sizing is essential, especially in humid regions where short cycling of air conditioning equipment can result in inadequate humidity control. Additionally, larger systems demand more fan power for the blower due to higher operating duct pressures. They are determined to design heating and cooling loads based on the building envelope, including the wall, ceiling, window, floor area, insulation value, and insulation thickness. Building orientation, roof surface color, and occupancy can also make a difference. About this topic, several authors investigated this matter.

Mathew et al. [47] stated that ventilation is frequently the major component of energy use. Numerous codes and standards specify a range of acceptable minimum ventilation rates. The goal is to identify an optimal ventilation rate that is safe and efficient in handling the worst-case scenario. He supported decreasing ventilation rates during unoccupied periods, as the ASHRAE Design Guides indicate. They also highlighted that loads are commonly overestimated as a result of designers' frequent adoption of high-utilization design assumptions. Due to part-load operation inefficiencies, this results in oversized HVAC systems, increased initial expenses, and higher energy consumption.

Djunaedy et al. [48] assert that HVAC systems are frequently oversized by design engineers on the grounds that a reasonable safety factor is required to manage periods more intense than the specified design circumstances. By minimizing their professional risk, the design engineers effectively force the facility owner to spend an immediate penalty for the increased initial cost of equipment and a continuous penalty for maintenance and energy consumption consequences. Usually, the client is not informed of the matters related to excessive safety factors. The article suggested that a cost analysis should be performed to assess the economic benefits.

Woradechjumroen et al. [49] address the significance of HVAC equipment oversizing in commercial buildings using data from long-term field observations. Retail stores are used as a representative example of typical commercial buildings in order to assess the condition of equipment oversizing and its impact on energy usage. The study can determine the level of oversizing and quantify the average energy penalty associated with sample buildings. Additionally, designers can utilize the findings as a benchmark for evaluating building load design.

Huang et al. [50] postulate that with no reliable data at the design phase to forecast peak load demand and insufficient operational experience to predict system operating costs or energy performance, uncertainty occurs in the sizing of HVAC systems. Into this basis, a new sizing methodology is formulated that considers the life cycle of HVAC systems when determining the ideal size based on several performance indicators and client preferences.

2.3 Building Envelope

It is well-known that building envelopes have a great impact on building thermal performance; thus, it should incorporate moisture and heat transfer control in hot-climatic regions [51]. Additionally, the building envelope has a significant impact on both energy consumption and peak loads. As the envelope's insulating characteristics deteriorate, energy usage and peak loads increase. This thermal layer should provide effective resistance to heat flow through the building structure, which can be achieved by choosing the appropriate insulators [52], phase change materials [53] or adaptive façades [54]. Building cooling demands can be significantly reduced in hot environments when thermal insulation [55], double-skin façades [56], or Energy Conservation Measures [57], are implemented, but the most common measure is the addition of thermal insulation coatings in opaque façades. It is also possible to optimize envelope attributes by modifying the wall, roof, or glazing designs in one-parameter increments using simulation models and building load estimations [58]. A series of techniques are being developed to build energy models that simulate a building/plant model for forecasting loads or cost benefits [59].

Sadineni et al. [60] assert that by implementing energy efficiency methods, the energy demand of buildings can be greatly decreased. The past decade has seen a resurgence of interest in energy-efficient buildings, owing to ecological challenges and the rising cost of electricity. In this context, several building envelope technologies are reviewed. The authors claim that energy utilization in Greece decreased by 20–40% as a result of thermal insulation, while using an energy-efficient building envelope in the subtropical regions of Hong Kong conserved up to 35% and 47% of overall peak cooling consumption, respectively.

Ascione et al. [61] investigated the critical application in the field of energy demand for air-conditioning healthcare facilities. The thermophysical characteristics of the building envelope in the Mediterranean climate are scrutinized for potential energy savings. The indoor comfort conditions were examined, as well as the minimization of energy consumption depending on the HVAC system. Retrofitting the building envelope is always a good idea from a variety of perspectives, including energy savings, improved internal microclimate, emission reduction, and technical and economic efficiency. Even when ventilation loads are significant, refurbishing the building envelope is an effective retrofit option.

El-Darwish and Gomaa [62] investigate energy efficiency in Egyptian educational buildings. They intend to propose a retrofit approach to enhance energy performance in a hot-arid region using DesignBuilder. Polystyrene insulation with 50 mm thickness and Low-E double glazing along with airtightness and 0.5 m external shadings were examined. The findings indicate that about 33% of energy savings could be achieved utilizing these strategies.

Castro et al. [63] assert that because the built environment is the major consumer of energy in the European Union thus, this utilization should be decreased across both new and existing constructions. A decision matrix is issued for determining the optimum practical retrofit steps for a present education facility using the Visual DOE 4.1 dynamic simulator. Three upgrades have been investigated under Gijón's climatic classification, Spanish normative standards, and the building layout. These three solutions are insulation addition, glazing renovations, and shading devices implementation. They concluded that the scenario with the optimum glazing with only intermediate façade insulation for the educational facility is the optimal upgrading option based on the majority of cost functions examined.

2.3.1 Thermal Insulation

Thermal insulation is critical for enhancing energy performance. Good thermal insulation results in a reduction in energy consumption and thus reduce environmental impact. Accordingly, it is critical to insulate the entire facility correctly to reduce heat gain/loss through the building envelope. The optimization of the thermal insulation thickness must be carried out based on the energy savings produced throughout the building life cycle compared to its total cost [64,65]. For this, it is necessary to take into account different factors such as the type of building, use, volume, orientation, thermal properties of materials, climatic conditions, type and efficiency of the air conditioning system, or energy costs [66,67]. Numerous studies have been undertaken in this manner by scholars and researchers worldwide.

Moujaes and Brickman [68] investigate the performance of a reflective painting used consecutively to a building in the southwest United States' hot-arid climate. The simulation is fed climatological data from a record, including hourly data on ambient temperatures, insolation, cloud cover, and so on, for the specified site. This model indicated that when the reflective paint is used solely on the roof, an 11% savings would be obtained in the summertime.

Al-Homoud [69] claims that buildings utilize a significant amount of energy throughout all nations. In areas with extreme climatic conditions, a considerable portion of the power is used to heat and cool buildings. This heating and cooling load can be decreased in a range of methods, the most significant of which is appropriate design and selection of the building envelope and its materials. The effective use of thermal insulation in buildings reduces the size of the air-conditioning system and byproducts the annual energy costs. Additionally, it extends the times of thermal comfort without the need for mechanical air-conditioning during the inter-seasons. Heating and cooling costs can be reduced by using thermal insulation in different types of buildings, as well as different types of insulation materials.

Yilmaz [70] states that in hot and dry climates, the walls and roofs' heat capacity should be maintained as it has a significant influence on utilizable energy. The author indicated that dynamic heat transfer modeling should be assessed throughout the design stage, especially in regions based in continental climates. During this design stage, the performance of the building envelope, as a function of its thermal mass, to regulate the passage of the thermal waves into the structure should be considered.

Bolatturk [71] found that one of the most effective methods to save energy in a building is through the use of insulation materials. He proposed that various engineering investigations should focus on determining and selecting the insulating thickness. Climate has an impact on the design of wall constructions. In hot areas, thin plaster layers are applied to bricks or concrete bricks; sandwich walls are employed in cold climates. In the study, he uses extruded polystyrene board as an insulation component. He concluded that the ideal insulation thickness of polystyrene boards in buildings ranges between 3.2 and 3.8 cm.

Anastaselos et al. [72] investigated thermal insulation in Greece. The assessment findings generated by their self-developed tool can be presented in the form of a simple rating system, allowing users to make extensive comparisons between numerous building materials and thermal insulating options. According to their findings, there was an overall energy decrease of around 17%. Finally, the use of composite external thermal insulating materials be encouraged in terms of energy, environmental, and economic factors was recommended.

Hyde et al. [73] postulate that high energy-efficient buildings are presently a target for sustainable commercial buildings. As a primary concern, this aim can be achieved in either new construction or retrofit existing facilities. Following an investigation, it is concluded that new conceptualizations are necessary to map particular carbon emissions for the various components of the entire energy system. In four projects, the NZEB strategy is investigated. It is claimed that retrofitting is important to decrease global CO_2 emissions. Of these case studies, some contended that significant energy efficiency improvements and considerable retrofit are required to maintain a sustainable level of energy consumption and reduce biomass demand. While other case studies have explored methods to attain ZEB emissions through a tiered approach of first improving energy efficiency, but the inability to incorporate renewable energies on-site limits the possibility of reaching a site NZEB.

Sharma [74] discussed some current breakthroughs in building energy. The low energy buildings have attracted global interest and are currently regarded as the upcoming building concept. Since such structures are now the focus of attention, significant developments in this field are reported. This study comprehensively reviews the research on the zero (or near zero) energy building envelope materials. This article presents a complete description of the zero energy building envelope materials and potential advancements for the benefit of building developers and designers. It aims to provide the most up-to-date information on various building envelope components such as insulation materials, walls, roofs, windows, doors, and glazing from a perspective of energy efficiency. Renewable integration, mostly photovoltaics, within the building envelope is also considered in terms of meeting the operating energy requirement and accomplishing the Zero Energy Building aim. Finally, he emphasized the need for research into the economic viability of numerous strategies for boosting the energy efficiency of buildings.

Elsafty et al. [75] have evaluated the reduction of energy demand in commercial facilities in Egypt and their environmental impacts. HVAC usage has been studied since Egyptian commercial buildings utilize a substantial amount of energy. Research work was performed in order to use insulation to minimize the energy usage of the HVAC system. The reductions in HVAC energy use assisted in reducing surplus energy consumption in Egypt during peak summer days. Using self-developed software, the authors discovered that the addition of insulation resulted in a 15% reduction in annual HVAC energy consumption, as well as a reduction of 7.78×10^{-7} tones CO_2 emissions per kWh saved.

Pargana et al. [76] declare that insulation is a viable technical approach in reducing building energy use. In this article, the authors assess the environmental implications and energy consumption of conventional thermal insulation materials such as extruded and expanded polystyrene, polyurethane, expanded cork agglomerate, and expanded lightweight clay aggregates. They concluded that insulating materials have proven to be a viable strategy for reducing energy consumption and assisting in constructing sustainable buildings in Portuguese conditions.

Delgarm et al. [77] used EnergyPlus models to conduct an optimization assessment in four different Iranian climatic conditions, with the annual illumination and cooling demands as the objective functions and the design constraints being the building orientation, glazing dimensions, and overhang configuration. The ultimate ideal arrangement reduces annual total building energy usage by 23.8–42.2%. Findings reveal the impact of weather conditions and architectural parameters in minimizing building energy use. In order to attain this goal, the proposed optimization strategy can be a very strong and valuable tool in the early stages of a building design, facilitating decision-making process.

Al-Saadi et al. [78] focused on determining the feasibility of energy-efficient retrofit practices for Oman's residential buildings. A pre-existing residential facility in a hot climate was chosen as a case study. DesignBuilder has been used to generate a building simulation model. Afterward, the model was validated utilizing actual electrical bills and meteorological conditions from 2014. Various energy-efficient retrofits schemes were examined using the validated model, including enhancing the air conditioner's efficiency, insulating both the walls and roof, upgrading to LED lighting, and improving the house's airtightness. The study concluded that by combining the best strategies from each category, the building's annual energy consumption could be decreased by up to 42.5%. The paper highlighted that adding polystyrene insulation to building envelopes resulted in a yearly energy savings of about 18%. This substantial decrease in energy usage can assist policymakers at governmental bodies and property owners in advancing large-scale retrofit campaigns to address the present environmental crisis related to increased energy use.

Aditya et al. [79] conducted a comprehensive review of the various insulation material employed in buildings. The manuscript classified the heat transfer properties of insulators into different classifications: 1) mass insulation, which includes materials that reduce heat transfer by conduction; and 2) reflective insulation, which reflects radiation heat owing to low emittance reflective surface, limiting heat transfer from one side to the other. The researchers postulated that in dealing with the issue, thermal insulation is such an efficient strategy that utilizes energy to assist in providing the needed thermal comfort due to its environmentally friendly characteristics. With increasing the thickness of the insulating material, the thermal conductivity is then reduced. Still, the insulation cost will rise until it outweighs the savings, where at the point the extra added thickness will provide no economic reward. As a result, there is an optimal insulation thickness in which the savings begin to decrease as the thickness of the insulating increases. The paper highlighted that building insulation is indeed a strategy of conserving resources and minimizing the detrimental environmental consequences of the greenhouse gases emitted by buildings.

Albardy et al. [80] begin their investigation by assessing the present state of Egypt's built environment and energy industry, focusing on energy consumption patterns and the inefficiencies that contribute to these trends. The observational part of the research relies on simulations to assess the postulated methodology by implementing it in an actual residential facility. Residences in Egypt have low insulation levels, which mean that more energy must be used to maintain a comfortable environment indoors. Utilizing a cost analysis, the authors suggested introducing polystyrene boards to building envelopes in Egyptian residential buildings.

Zhang et al. [81] concluded in their research that painting external walls with high-reflectivity materials is an efficient technique to reduce the heat absorption of solar energy and thus energy usage. The authors found that painting exterior walls with reflecting coatings can reduce around 15% of summer energy use. Additionally, economic assessment and analysis reveal that this coating material is highly beneficial to southern Chinese cities. The payback period is faster due to the increased cooling energy savings during the hot season.

An-Naggar et al. [82] stated that the proportion of energy used in buildings increases yearly due to a variety of causes, the most notable of those is the increase in the number of air conditioning systems installed and their operational durations. The article investigated the impact of wall and roof insulation on energy demand and CO_2 mitigation in Egyptian residential buildings using the DesignBuilder simulation tool. The article concluded that by employing thermal insulation in the walls and roof of the last floor, a drop of nearly 40% of the energy used by the HVAC could be achieved; such reductions constitute a considerable operational cost saving compared to the uninsulated envelope.

López et al. [83], with the aid of simulation tools, analyzed in this article different refurbishing measures to the University of Oviedo's Energy Department Building through a series of models. The presence of insulating materials to the outer facades is one of the measures to upgrade the building envelope was stated. Adapting effective refurbishment procedures to the climatic conditions and making that permissible in the construction standards is also highlighted. Moreover, the study concluded that the façade adjustment could save around 3% of the building's overall energy use.

Evin and Ucar [84] investigated applying thermal insulating materials to four residential property building envelopes in four different meteorological regions in Turkey. They tested various insulating materials, including extruded polystyrene (XPS), expanded polystyrene insulation (EPS), Rockwool (RW), and polyurethane (PUR). The researchers observed that when the roof is insulated with XPS, the cost of energy is significantly less than when the roof is not insulated. Finally, the authors suggested that the same methodology be used in other types of buildings and different climatic zones.

Raimundo et al. [85] intended to determine the optimum energy-efficient and cost-effective thermal insulation solutions for buildings in Portugal. Five distinct facilities were chosen: an apartment, a standalone house, a private clinic, a private high school, and a medium-sized marketplace. These facilities were located in different sites that reflect the whole range of meteorological conditions in Portugal's temperate environment. Researchers found that EPS (Expanded Polystyrene Insulation) is the most significant cost-effective thermal insulation material and is best used in the building envelope's midsection.

Verichev et al. [86] postulate that maintaining the energy performance of homes in the event of climatic change is tough, particularly in nations where construction standards control the maximal amount of energy a facility can utilize. As a result, to plan future developments, building standards should be reviewed and adapted to the scope of energy efficiency. In Chile, authors used a simulation model to estimate the thermal transmittance of single-family outside walls and the optimal thickness of thermal insulation materials in terms of energy efficiency. The scholars claim that by constructing a home with energy efficiency in mind, carbon footprint might be reduced by 20%.

2.3.2 Building Integrated Photovoltaics (BIPV)

Buildings utilize a significant percentage of worldwide energy consumption and play an essential role in greenhouse gases; therefore, various initiatives have been considered to reduce energy and emission levels from buildings, particularly through energy alternatives [87,88]. In warm/hot regions, photovoltaics (PV) appropriate space accounts for around 60% of the total rooftop area in commercial properties [89]. Due to the widespread installation of HVAC equipment on most roofs in hot climes, but this can be difficult to achieve. So, building-integrated photovoltaics (BIPV) is one of the viable green solutions worldwide. A BIPV installation is composed of PV panels incorporated into the building envelope/skin to produce electricity.

Hammond et al. [90] used energy analysis, environmental life-cycle assessment (LCA), and economic assessments to investigate the performance of a residential BIPV. In an energy assessment, it was observed that the model repaid its investment in 4.5 years. LCA indicated that the embodied consequences were compensated by the energy produced, leading to a net ecological impact in most categories. The findings clearly highlight the significance of the new governmental funding plan for the future adoption of BIPV in United Kingdom.

Ng et al. [91] postulate that the built environment utilizes a considerable portion of energy. The manuscript affirms that semi-transparent BIPV is a viable solution for enhancing building energy efficiency. This article investigates six commercially semi-transparent BIPV glass panels, four of which are single-glazed and two of that are double in the Singaporean market. Additionally, the authors were opposed to more conventional glazing options such as single-glazing, double-glazing, and low-emissivity glass. The findings indicated that semi-transparent BIPV might be adopted among all orientations in tropical nations such as Singapore. Within the intended scope, the study demonstrated the possibility for semi-transparent BIPV to replace glazing façades. BIPV panels exceed all other widely used glazing systems in terms of energy efficiency.

Shukla et al. [92] assert that building integrated photovoltaic (BIPV) technology is feasible, novel, and promising for net zero-emission buildings. PV is widely predicted to expand significantly to mainstream energy generation during the next decade. BIPV technology turns a facility from an electricity user to an electricity generator. This article concludes that BIPV panels may be easily integrated into a building's façade due to their large surface area. Finally, the manuscript emphasized the importance of convincing building designers that BIPV solutions are viable alternatives to other construction materials.

Biyik et al. [93] remarked in their review that the EU's aimed for a 20% share of sustainable/renewable energy resources in energy needs by 2020. Many renewable energy studies have been committed to photovoltaics that use solar radiation to produce power obtaining a significant attention as a PV technical solution in the last decade. It has been demonstrated as a viable green energy generating technique to assist facilities in partially fulfilling their demand. The researchers advocate that using simulations and computational scenarios, it is easier and less expensive to evaluate performance, power generating capability, energy potential of the façade, and analyze energy consumption levels. Among available simulation tools, TRNSYS and EnergyPlus are the two widely used. Finally, the authors supported that investing in BIPV is a viable solution.

Shukla et al. [94] research BIPV within the Indian region, which is vast and receives a high amount of average solar irradiation. Authors assert that India's energy policy was shaped by the country's intention to secure energy supplies and a broader aim of achieving energy self-sufficiency. According to the National Manufacturing Policy, solar power is a strategic industry among the sectors of particular concentration. Therefore, the researchers advocated for modifications in construction codes to facilitate the implementation of BIPV technologies in the development of new buildings. The article emphasized that the BIPV technology provides an alternative clean energy model for smart cities and is a crucial step toward a sustainable emerging nation.

Sorgato et al. [95] research the trends for sustainable construction to decrease energy use while also attempting to meet their local energy requirements by self-generation in Brazil. The scholars believe that any project should be developed with sustainability in mind. A passive method in line with the energy generating possibilities of facades and roofs should be investigated. The paper intended to assess the economic and technical viability of upgrading standard façade materials such as conventional glass via glazing integrated PV (GIPV) systems to a commercial facility's façade and roof in six Brazilian cities. The manuscript concluded that upgrading ordinary façade construction materials using PV modules is an innovative yet cost-effective solution.

Farghaly and Hassan [96] state that building envelopes play a considerable influence in lowering energy utilization, particularly in hot climates, due to the wide variety of envelope components and innovations that have been produced. BIPV solutions, outlined in their article, might be used to minimize energy usage by integrating into the building's external skin. In Cairo, Egypt, the authors evaluated renovating a section of an existing wall employing the DesignBuilder energy simulation tool. Following a feasibility study, the researchers concluded that in Egypt, derived by the hot climate and solar irradiation, BIPV has considerable energy saving percentages and a quick payback period.

2.4 HVAC and Built Environment

Nearly half of the overall energy consumed in commercial buildings is spent on HVAC systems [59,97,98]. Therefore, engineering and design firms should propose cost-effective solutions for energy management in order to optimize air conditioning systems and, as a result, preserve the environment from global warming and climate change. Another crucial parameter is the HVAC and human health relation, with special focus on the airborne transmission. COVID-19 epidemic and mucormycosis infections were clearly related to the dissemination of infectious aerosols in indoor environments among humans, highlighting the importance of strict and effective measures to control the spread of pathogens [99]. Based on available data, the COVID-19 disease is primarily transmitted across humans through respiratory aerosols and interactions [100–104]. SARS-Cov-1 and MERS-CoV spreading was believed to be facilitated by HVAC equipment which was not designed to handle infected residents [105]. Thus, identifying indoor environmental quality measures is essential. According to several studies, proper ventilation and indoor relative humidity are the deriving factors in viral survivability [99,106]. Proper ventilation does not only reduce the risk of aerosol transmission but also improves air quality (IAQ) and maintains CO_2 levels within acceptable parameters. While it has been recommended that maintaining indoor relative humidity (RH) between 40-60% help in reducing viral dissemination and survivability [107–109], the large amounts of outdoor fresh ventilation air may cause humidity control challenges in some locations.

Korolija et al. [110] examine the impact of building characteristics and HVAC systems on energy efficiency and the environment. The purpose of this examination is to aid in making HVAC system decisions for office buildings in the United Kingdom. Several parameters affecting heating/cooling energy usage are varied through the EnergyPlus simulation tool (e.g., insulation, HVAC system, supply air temperature setpoint, and outdoor air supply). The VAV and CAV systems, for instance, are evaluated by means of their energy usage. VAV systems are generally more energy-efficient than CAV systems. Systems fitted with an airside economizer that regulates the outside air's amount in response to heating and cooling needs and weather conditions have demonstrated considerable benefits over constant outside air systems. VAV systems with economizers and higher air volumes yield the lowest yearly energy utilization when coupled with the best practice degree of insulation in the building envelopes.

Vakiloroaya et al. [111] reviewed various HVAC energy-saving techniques. The article reported that discovering new techniques to minimize energy use in buildings without sacrificing comfort or indoor environmental quality is a research challenge that is presently ongoing. The authors indicated that a useful strategy for increasing energy efficiency has been creating HVAC system combinations that incorporate various conventional HVAC system components. For instance, a reconfiguration may enhance the system's functionality and hence its energy-saving possibility, but at the system's initial expense. Thus, the operation of a newly designed system must result in sufficient energy reductions to justify the original expense within a reasonable timeframe. The necessity of cooled outdoor air in the buildings is yet another factor that significantly affects the energy consumption of HVAC systems. The activity type itself in a building affects the amount of fresh air that should be provided. Consequently, optimizing fresh air flow rates depending on the design standards is a quite effective means. Owing to the complexity of deciding, designers should consider and implement the most effective energy efficiency solutions while taking into account all technological, economic, and applicable factors.

Kim et al. [112] perform comprehensive energy simulations to compare the performance characteristics of a dedicated outdoor air system (DOAS) and a VAV desiccant-enhanced evaporative air conditioner (DEVap) in a built environment. Through supplying dehumidified cool outdoor air into a zone and incorporating a ceiling radiant cooling panel (CRCP) parallel unit targeted at handling the remaining sensible load, the DOAS successfully takes latent cooling loads and a portion of the space's sensible cooling loads. Finally, the article concluded that compared to the DEVap system, the annualized energy analysis shows that the DOAS running in parallel with a CRCP system utilized 22% lower primary energy.

Wei et al. [113] postulate that upgrading existing buildings towards improved energy efficiency is highly demanded due to the significant percentage of building energy use. A growing amount of focus has been placed on the connection between indoor air quality, employee productivity, and long-term health and well-being. A corporate office building featuring a retrofitted HVAC system was assessed for both energy utilization and indoor air quality. Building management sensors, outside air dehumidification, and a two-stage particle filter system were all involved in the retrofitting process. Energy records were obtained prior to and following the retrofitting. By integrating all of these strategies, the upgraded HVAC system could lower energy consumption by half while preserving mainly acceptable indoor thermal conditions.

Yildiz et al. [114] concentrate on airport terminal facilities considering they utilize higher energy than other facilities in an airport due to their operational characteristics. A considerable percentage of the annual energy use in terminal buildings has been impacted by HVAC, particularly in severe environments. Several approaches might enhance existing terminal facilities to minimize their energy usage and CO_2 footprints. The intention is to investigate and analyze the influence of different energy-saving measures on energy usage and CO_2 emission levels, involving several adjustments to the HVAC system used in airport terminal facilities. Building energy simulations were employed using DesignBuilder to analyze and evaluate energy usage, cost reductions, and ecological advantages at a Turkish airport in the country's coldest regions. The authors asserted that upgrading from Constant Air Volume (CAV) to Variable Air Volume (VAV) was determined to be economically unfeasible in Turkey's cold environment. The manuscript remarked that adjusting setpoint temperatures and replacing conventional pumps with variable speed pumps are among the most energy-efficient, cost-effective, and environmentally friendly alternatives.

Mihara et al. [115] stated that standard AC systems struggle to offer the desired thermal comfort in practice. The authors conducted surveys and questionnaires to assess humans' comfort conditions, perceived air quality, and energy usage in different zones of a higher education facility. One features a Dedicated Outdoor Air System coupled with ceiling fans (DOAS-CF), while the second is a traditional Fan Coil Unit (FCU). Through their behavioral adjustment in selecting their seating place depending on their thermal and air motion preferences, residents under DOAS-CF at 27 °C were relatively thermally comfortable. They indicated better thermal acceptance than those with FCU at 24 °C. In conclusion, the authors suggest that when occupants' behavioral adaptability is granted, the DOAS-CF system accomplishes improved thermal comfort; it moreover attains higher energy saving than the typical mixed AC system, with approximately 27.7% less energy than FCU.

Pan et al. [116] analyze the proper HVAC operations in facilities from an engineering viewpoint to maintain a healthy and clean indoor condition, as well as to address the mitigation of COVID-19 transmission indoors. Researchers believe that since fresh air is safe, introducing more outdoor air can aid in minimizing the concentrations of contaminants indoors and prevent viral transmission in an enclosed space. It also emphasized that ensuring that each room receives adequate ventilation is a top priority for any HVAC system. Finally, they emphasized the importance of adaptable design in anticipating the demands of unexpected crises such as pandemics, including the consideration of higher quantities of fresh air supply in the HVAC design.

Guo et al. [117] state that numerous organizations and societies all over the world have released guidelines regarding coronavirus infection (COVID-19) and virus (SARS-CoV-2). Although all recommendations emphasize the necessity of ventilation, the ventilation rate which could minimize the risk of aerosol particulate transmission has not been determined. As per the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) and ASHRAE recommendations, the authors advise increasing the quantity of external air in ventilation systems and opening the minimum outdoor air dampers high as 100% if practicable, and disabling demand-controlled ventilation. The authors emphasize the importance of switching to 100% outdoor fresh air for air handling units with recirculation, even those designed with return filtration systems since pathogens in return ducts could perhaps re-enter a building.

2.5 Research Gaps and Aim

Previous research has shown that energy efficiency is a vital research area that policymakers are pursuing; nonetheless, it is often disregarded in various underdeveloped nations. To the author's knowledge, the literature demonstrates a research deficit in energy saving in various hot climatic regions like Egypt. Whenever an energy-saving strategy advocates for solutions that minimize energy utilization, operating costs, and environmental impacts, the ensuing interior thermal comfort intervention and air quality should be incorporated into the decision-making framework, developing a holistic approach that considers all the various aspects of efficiency may aid decision-makers during the planning and retrofit phases. This dissertation presents these parameters quantitatively for a variety of energy-efficient alternatives. Additionally, it illustrates how it may be applied through an enviro-economic analysis and the associated thermal comfort, as determined by Fanger PMV and DCH, on a current institutional educational facility in three ASHRAE climate regions in Egypt represented by three cities, Aswan (Zone 1B, Very Hot-Arid), Cairo (Zone 2B, Hot-Arid), and Alexandria (Zone 2A, Hot-Humid).

The author aims to close this gap by proposing a strategy that incorporates numerous parameters impacting energy performance throughout the decision-making process for an optimum efficient design solution for building owners and authorities, in line with Egypt's vision 2030 [118]. Relying on parametric analyses that incorporate multiple cost functions (demands, costs, comfort), this methodology assists create a decision matrix that may be utilized for defining energy efficiency normative and policies and standards for buildings' new designs and retrofits in Egypt.

3. METHODOLOGY AND CASE STUDY

This chapter describes the methodology applied in the simulation process of the study cases, details the characteristics of the theoretical models as well as the economic assessment, and specifies the validation method used to quantify the reliability of the theoretical model. Finally, a sensitivity study is carried out to identify the most influential factors that will be analyzed in the next chapter.

3.1 Building Energy Simulation (BES)

Climate change, depletion of fossil fuels, increasing occupant demands and comfort levels, as well as spreading awareness about the correlation between indoor environments and occupant productivity, are just a few of the interactions that should be taken into consideration in investigations and research studies [119]. Buildings are dynamic systems, and to perform an appropriate Building Performance Analysis (BPA), both the analyst and the tool must recognize and account for the changing interdependencies between various components over time. A complete and integrative subsystem methodology is needed to yield sustainable facilities and system approaches that satisfy future demands, as demonstrated in Figure (3-1).

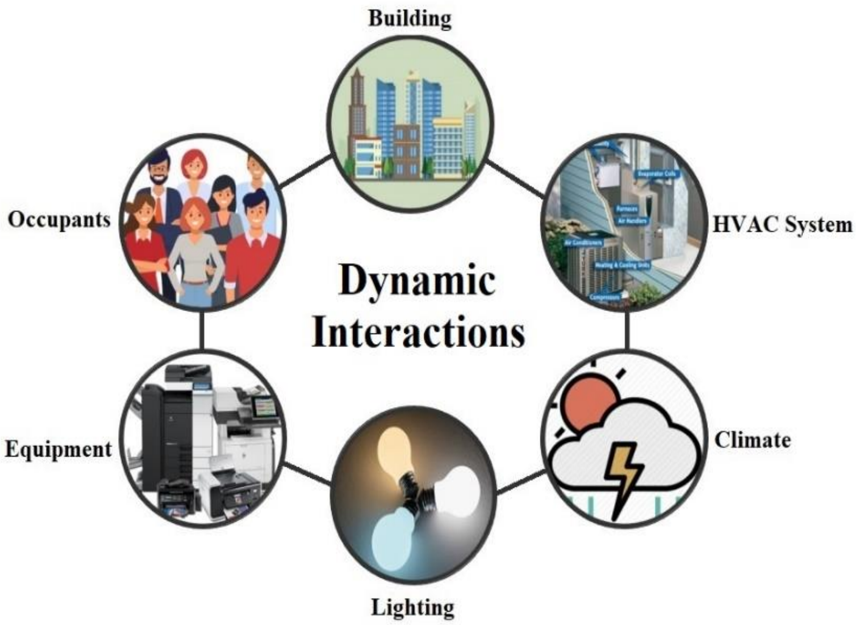

Figure 3-1. Dynamic interaction of building components [22]

Building Energy Simulation (BES) mainly employs physical techniques to estimate building performance energy utilizes, analyze design ideas, examine code compliance, and rate buildings depending on benchmark rating standards, among other potential possibilities before construction and refurbishment [120–122]. When it comes to forecasting and predicting building efficiency and performance, the core is energy dynamic simulation. Many demanding high-performance construction criteria and retrofits can currently be addressed using simulation-based modeling [123].

Buildings consume energy for various purposes, including HVAC, illumination, appliances, plug-in, and additional miscellaneous loads. Many of these uses could be predicted relying on scheduled timings as lighting schedules, equipment, and appliances operational schedules. Oppositely, HVAC systems depend upon the climate and internal heat gains daily and hourly. As a result, it may become more challenging for energy simulations to take into account the thermal reaction of a building's needs and to predict both the operational and functionalities of the subsystems that respond to these demands. Furthermore, HVAC models in building simulations often produce energy utilization outcomes that enable building performance enhancement.

Developing a BEM that accurately replicates the dynamic thermal behavior requires an in-depth understanding and exact mathematical description of how the building operates and interferes with its environment [97]. Alternatively, another individual may develop BEM with enough data using no heat transfer formulas or thermal or geometric variables. The synthesis of both methods is also practicable, where a hybrid model can be built based in part on physics and in part on statistical information.

The energy performance is governed by heat and mass exchange processes, described by a coupled mathematical function with time dependence. The mathematical resolution of these energy flows can be solved using numerical simulation tools. There is a wide variety of numerical modeling programs available today, characterized by different levels of detail and precision depending on the physical processes they solve. The most common energy simulation programs can be classified as physics-based (white box) simulations, empirical prototypes (black box), and in-between models (grey box models) [124–126].

3.1.1 White Box Modelling

White box, engineering methods, direct simulation models, or forward simulation methodology employs precise physical algorithms to analyze building assemblies, sub-systems, and mechanisms to estimate entire buildings and their different sub-system attitudes, including energy utilization and internal thermal comfort. Since the extensive dynamic formulas in white-box models, they have the proficiency in dealing effectively with building dynamics. Still, they necessitate extensive work to accurately develop and simulate a realistic building model.

These white-box models solve the mathematical algorithms that describe the physical processes based on the initial and boundary conditions. But, depending on the type of equations used to characterize the building energy performance, the control volumes, and the way of solving the energy equations, these models can be classified into three categories: nodal, zonal, and Computational Fluid Dynamics (CFD) [122]. The annual analysis of the energy performance of buildings, their components, and their energy systems with low-resolution frequencies is usually done using nodal models. This white-box modeling technique is widely adopted and used in current challenging simulation tools [127], such as ESP-r, BLAST, TRNSYS, DesignBuilder, and EnergyPlus, which could effectively manipulate building dynamics [128–133].

These simulation programs are generally considered during the planning and design phases of a building before it is built, refurbished, and even after construction to validate that the results were correct. They predict overall energy use, HVAC, operating scheduling, and lighting, among other things, depending on accurate physical qualities of facilities occupancy schedule, geographical environments, construction type, and climatic conditions [134–137]. Nonetheless, the existence of certain reliable data is challenging and, in some circumstances, difficult to gather. The Department of Energy (DOE) of the United States founded a variety of commercial building benchmark simulations, providing a standardized framework for building energy models [138]. Figure (3-2) expresses the nodal approach applied by building modeling tools to perform various investigations [139].

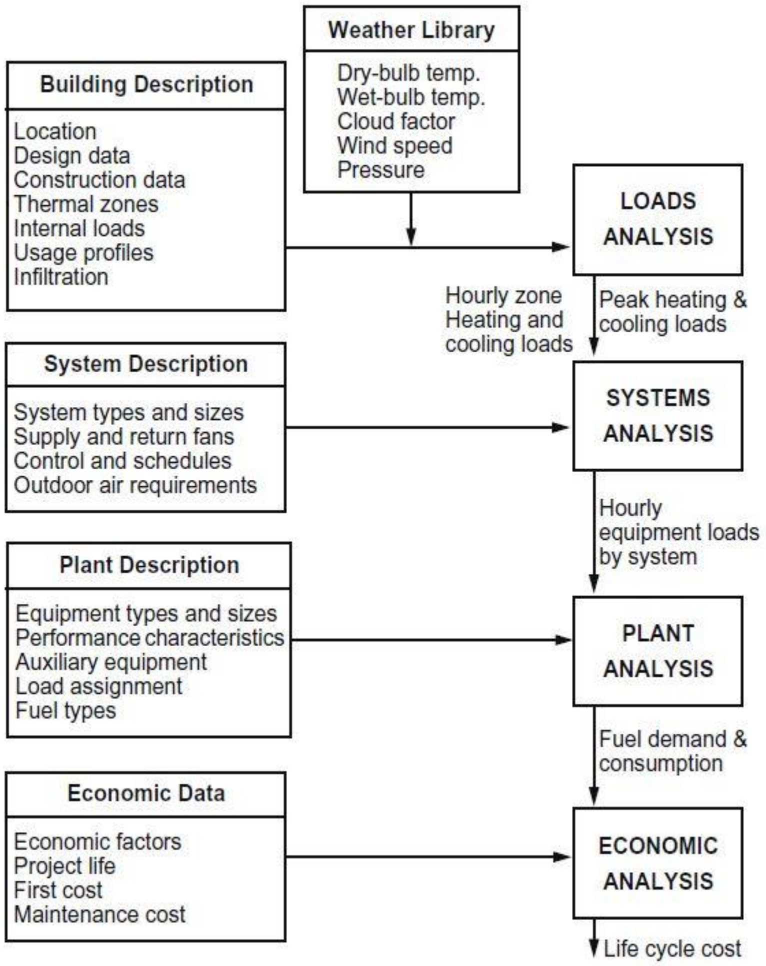

Figure 3-2. Energy Modelling Software Scheme [139]

A BES white-box model is typically developed using "first principles of building physics" and is regarded as a reliable, trustworthy model [140].

3.1.2 Black Box Modelling

The "black box” model, also known as statical models, refers to an entirely data-driven model used chiefly in buildings control solutions. The association between facility energy use and operational data is directly captured using statistical models [125]. This kind of simulation requires on-site data over a long enough duration to train the algorithms to forecast building performance under various scenarios. These approaches perform single or multiple variable regressions between consumption/demands and other input variables, thus requiring statistical models or artificial learning techniques to estimate the outputs [141]. Under this structure, the model parameters have an insignificant physical interpretation. Previous studies have used those black box concepts to establish building control practices to cut energy usage and costs. There are several drawbacks to using black-box approaches, including the need for a large number of training statistics to be able to forecast performance accurately, the absence of a clear and specific correlation between input variables and building physical parameters, the time-consuming requirements, as well as the need for re-training once building fabric or operating schedules are altered [133].

3.1.3 Grey Box Modelling

Energy systems within buildings can be simulated with grey box modeling, which uses reduced physical representations to represent their behavior [125,142]. Reduced datasets training and computation time are achieved by using reduced physical models. Data from the process is used to identify model coefficients via statistical or parametric identification approaches. The use of this type of simulation approach requires the physical interpretation of some of the model parameters. Some drawbacks are also noticed in grey box models as they need an extensive understanding of both statistical and engineering modeling, and extrapolation is only possible to account for the possibility of aggregating/simplifying input variables [133].

3.1.4 Selection of the Simulation Tool

Each of the numerical methodologies described above for the analysis of the energy performance of a building has its own field of action, depending on the physical processes studied, energy volumes, required precision, or the number of studied zones. In this thesis, building energy consumption, economic assessments, and indoor thermal comfort are quantified based on different construction and operational variables. In this case, the energy volume is the building itself. The required outputs are energy consumption, temperatures, efficiencies, and economic and environmental factors.

Therefore, the selection of the simulation model is based on these requirements: the global resolution of a uniform field, modeling in several zones, access to multiple constructive and operational inputs, short time-steps, dynamic initial and boundary conditions, and low computational needs. According to these necessities, the nodal model EnergyPlus has been selected to evaluate building energy performance dynamically. The model process has been carried out with de simulation program DesignBuilder.

3.2 DesignBuilder Simulation Tool

DesignBuilder is a very well-known and comprehensive user interface for EnergyPlus, the industry's leading building energy simulation engine [143,144]. EnergyPlus engine is modular in nature and utilizes a heat balance-based zone computation with time steps less than an hour [145]. Architects, designers, and scholars use EnergyPlus to assess energy demand, including HVAC, lighting, as well as plug and process loads in buildings [132]. Since its introduction in April 2001 as a unique tool based on both DOE-2 and BLAST energy simulation platforms, EnergyPlus has evolved into a comprehensive building, envelope, HVAC, and power generation simulation engine [146].

Within DesignBuilder, creating energy simulations may span from a single building element to a constellation of buildings [147]. It offers access to the majority typically demanded modeling capabilities, including those for the fabric of the building, thermal mass, windows, shading, renewable energy, and HVAC systems. Energy simulation requires the model and the use of pattern and meteorological conditions in the site to compute various outcomes, including peak loads, system size, and energy utilization for any chosen timeframe. This data may be used to forecast utility expenditures and perform economic analyses of alternative design methods. DesignBuilder is most beneficial in a) early design decisions, b) component or material selection, and c) retrofitting decisions. But to accurately forecast a building performance, several input data are required to feed the model. These data include:

a) Location and weather file (e.g., Longitude, Latitude, Climatic region, etc.)
b) Building geometry (e.g., Building zones, Shape, etc.)
c) Envelope components (e.g., Wall composition, Glazing systems, etc.)
d) Building services (e.g., Lighting, HVAC systems, etc.)
e) Usage of the building (e.g., Activity type, etc.)
f) Building shading elements and surrounding obstacles (blinds, overhangs, nearly buildings, etc.)

The simulation engine facilitates the geometrical model to interface with exterior weather, occupancy, and building system operation to estimate various loads occurring in the facility on an hourly basis. Computations are performed employing fundamental physical principles and energy balance formulas. The energy consumed by systems that generate heat as well as additional loads is also estimated in the same timeframe. The outputs of the processing are used in the computations for the following time step, as well as in the output file. This procedure is repeated throughout the whole simulation, and the final output is displayed as consolidated or on the specific period wherein the computation was performed. The simulation process is graphically illustrated in Figure (3-3). Further explanations of the computation algorithms are presented in detail [148,149].

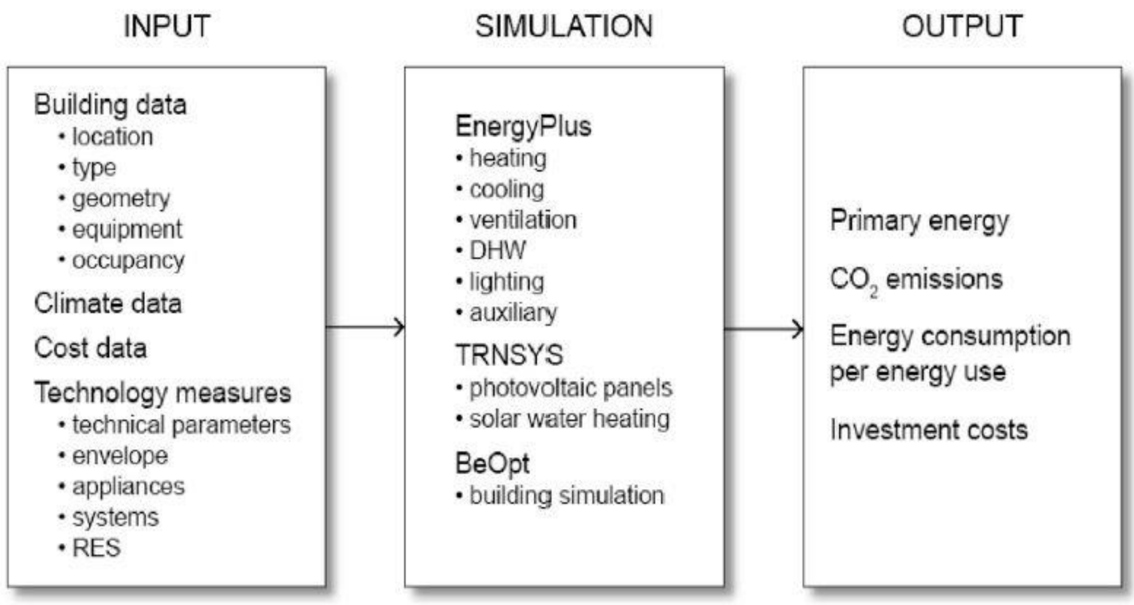

Figure 3-3: Energy Simulation Process [150]

3.3 Engineering Economics and Decision Analysis

In order to optimize the global performance of the case study, this project must be subjected to extensive economic analysis, such as any engineering project introduced by any design/consultation firm. The outcomes of this assessment should serve as a reference (possibly one of numerous) for identifying whether or not to pursue the proposal [151]. Simply, the purpose of the economic study is to give a foundation for executing an informed decision about a given project, particularly when several alternative ways exist for accomplishing the project's targets [151].

This subsection addresses cost assessment, clarifying the terminology used and demonstrating the assessment methodologies. The Net Present Value (NPV), Internal Rate of Return (IRR), the Return on Investment (ROI), as well as the Payback Period (PBP) have all been analyzed.

As the current value of money is worth more than the future, the NPV technique evaluates the present value of all expected cash flows obtained by a project, covering the original capital expenditure. This index measures the difference across the current value of cash inflows and outflows. A positive NPV implies that the estimated returns from an investment or project surpass the expected costs; consequently, an investment with a positive NPV is regarded to be worthwhile.

In economics, the IRR measure is utilized to estimate the profitability of proposed investments. An investment's attractiveness increases in direct proportion to its IRR. Since IRR is comparable across various investments, it is used to contrast a variety of potential investment projects on equal ground. Investments with the highest IRR are often regarded to be the best alternatives when evaluating investment solutions with comparable functionalities.

ROI is a metric used to assess the return on capital invested. Economically, ROI is a straightforward percentage that represents the difference between the net earnings (or losses) on an investment and the cost of the investment. Since it is presented as a ratio, it allows you to evaluate the efficacy or profitability of various investment options. Usually, the project with the highest ROI is beneficial and should be prioritized.

The PBP denotes the duration required to recoup the investment cost. This sort of analysis enables the comparison of various investment possibilities and the selection of the proposal that will repay the investment in the quickest period. The payback period is frequently employed as an analytical technique since it is simple to perform and understand for the majority of people. When all else is equal, shorter PBP is advantageous than longer ones. But, due to its substantial limitations, economists combine it with other measures such as NPV, IRR, and ROI.

In this theme, the proposed solutions undergo a full techno-economic assessment integrating the four metrics described above [7,151,152].

3.4 Methodology

According to the previous sections, the dynamic simulation engine DesignBuilder is employed to assess the energy efficiency of an institutional facility in Egypt. This tool can examine the energy assessment of the proposed retrofitting strategies, as well as the influence of the approach on the building's thermal loads. Considering Egypt's climatic zones along with the present building's construction and operating records, a baseline model relying on on-site real measured consumption is validated through ASHRAE validation practices. This verified and validated baseline model, used to estimate annual thermal loads, was used to execute an energy analysis methodology that allows evaluating the variables on the annual energy and peak design loads [153].

Correspondingly, the implementation of building envelope solutions was initially investigated. With this aim, a comprehensive set of simulations was performed, taking into account both the building's requirements and its normative constraints. A local sensitivity analysis was used to quantify the influence of each studied variable [154–156]. Only the retrofit variable is modified from the initial values within each simulation, with all other variables remaining unchanged. This series of simulations were developed focusing on data from currently existing retrofitting solutions in Egypt.

As HVAC accounts for a significant portion of a building's energy consumption, it is critical to assess and optimize its performance to accomplish global energy efficiency. Additionally, and in the context of respiratory infections prevention considering global recommendations, another investigation has been conducted focusing on evaluating HVAC solutions for improved indoor environmental quality with the vision of minimizing indoor infection and mold mitigation while also being energy-efficient and environmentally-friendly solutions.

Based on annual loads and environmental quality (CO_2) as well as thermal comfort, expressed in Fanger PMV and Discomfort Hours (DCH), this study identifies a methodology of multi-approach decision-making toward the selection of the most beneficial solution in terms of reducing energy consumption, mitigating CO_2 emissions, as well as improving the indoor thermal comfort.

The methodology proposed is graphically illustrated in Figure (3-4).

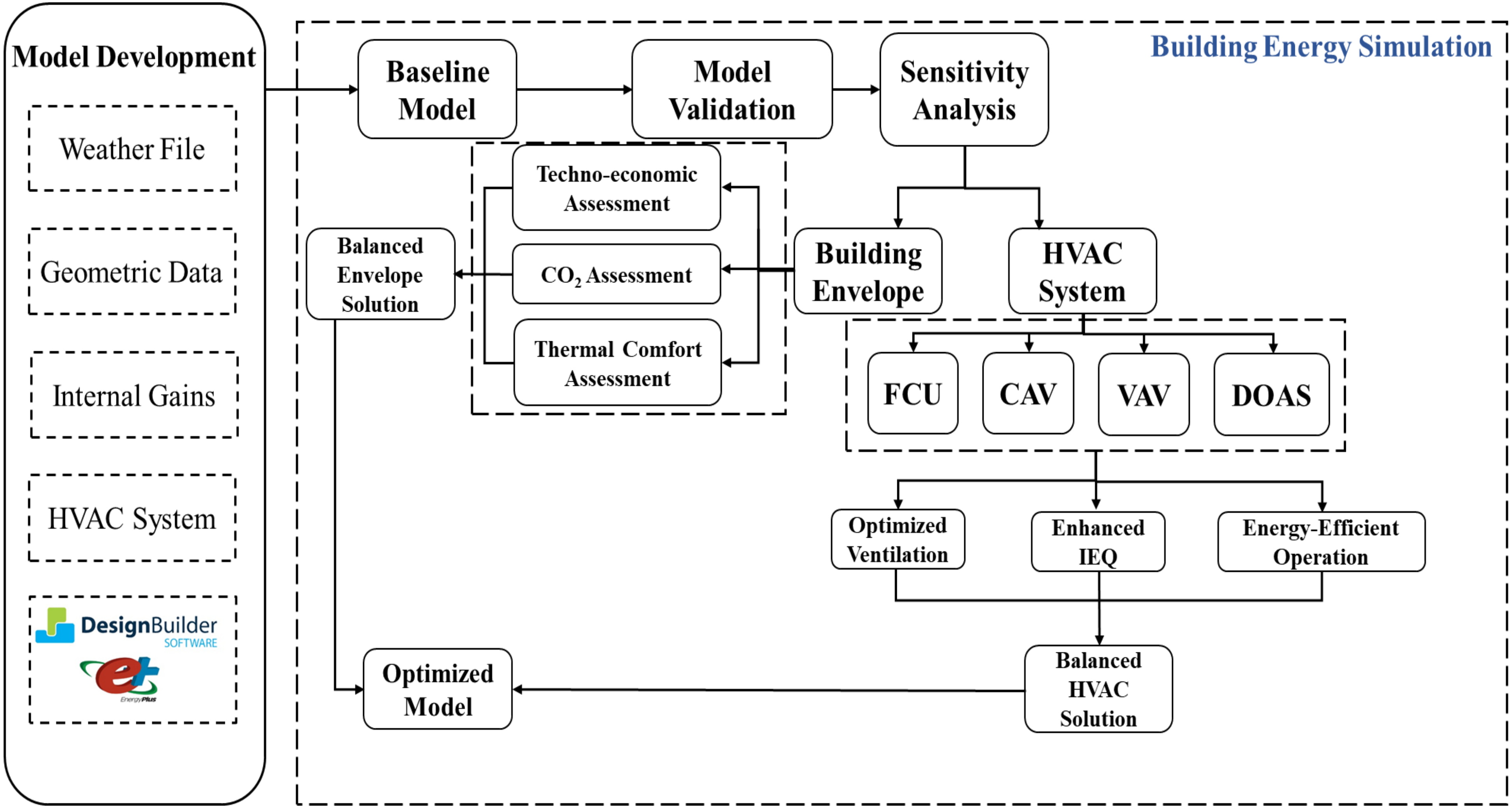

Figure 3-4: Graphical illustration of the proposed methodology

3.5 Case Study Description

The investigation considers an institutional facility in Cairo, Egypt as a case study model. All the required input data for the baseline model simulation as geometrical shape, envelope properties, internal activities, and gains, as well as building zones, is acquired from the facility management office.

3.5.1 Building Geometric Model

The case study facility is an institutional educational building in the New Administrative Capital City, New Cairo, located 35 kilometers east of Cairo, Egypt, as shown in Figure (3-5). The baseline model specifications are tabulated in Table (3-1).

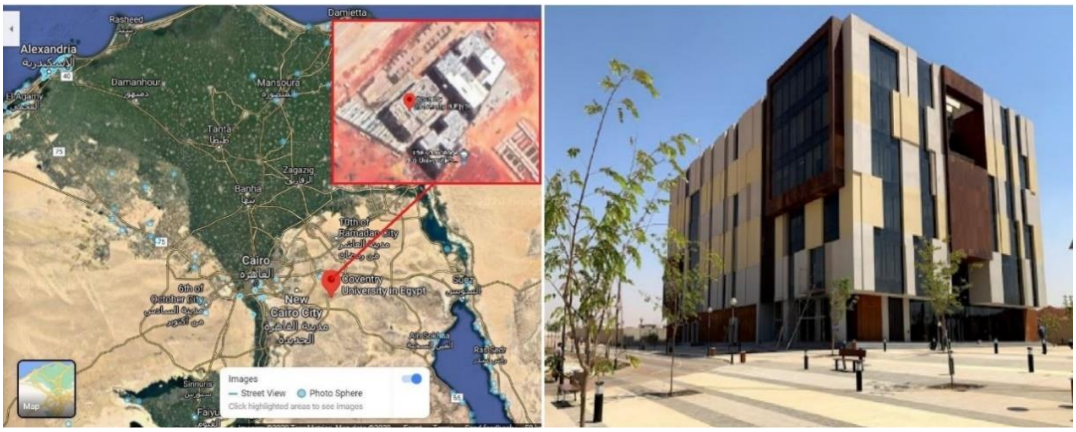

Figure 3-5: The Geographical location and existing model

The dynamic simulation model of the building, developed with DesignBuilder, is shown in Figure (3-6).

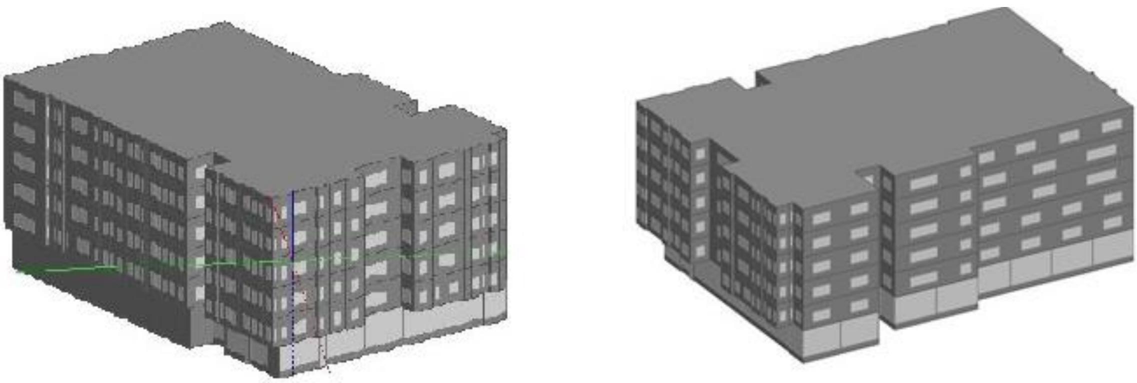

Figure 3-6: DesignBuilder geometric built-up model

Table 3-1: Baseline model specifications

	Item	Descriptions	Data Source
General			
	Vintage	Existing Building	As-built
	Location	New Cairo, Egypt	
	Building Type (Principal Building Function)	Institutional Facilities	As-built
	Building Prototype	Educational Building	As-built
Form			
	Total Floor Area (m^2)	11,350	As-built
	Number of Floors	6	As-built
	Zones	Call Center, Classrooms, Corridors, Labs, GYM, Lecture Halls Libraries, Lobby, Lounges, Meeting Rooms, Offices, Receptions, Restaurants	
Architecture			
	Exterior walls		
	U-factor (W/ m^2 °C)	1.924	As-built
	Roof		
	U-factor (W/ m^2 °C)	2.27	As-built
	Glazing		
	Window Fraction (Window-to-Wall Ratio)	Average Total: 30 %	As-built
	Glass-Type and frame	6 mm Double Blue Glass / 6 mm Air Gap	As-built
	U-factor (W/m^2 °C)	3.094	As-built
	SHGC	0.503	
Internal Gains			
	Occupancy density and ventilation requirements	Defined according to space type	ASHRAE Standard 62.1-2016
	Lighting and Plug loads	Defined according to the space-by-space method	ASHRAE Standard 90.1-2016
	Operating Schedules	8:00 to 16:30, five days a week	Operating Schedules – Facility Management Office

The building comprises several activities, and occupied zones tabulated in Table (3-2) indicate the percentage of each occupied zone.

Table 3-2: Occupied zones percentage to building total area

Zone	Area (m^2)	Area %
Call Center	43	0.5
Classrooms	693	7.9
Corridors	2253	25.8
Dry Lab	407	4.7
GYM	150	1.7
Lecture Halls	707	8.1
Libraries	466	5.3
Lobby	827	9.5
Lounges	453	5.2
Meeting Rooms	276	3.2
Offices	1584	18.2
Receptions	634	7.3
Restaurants	237	2.7
Total	8728	100

3.5.2 Climatic Data

Based on the Köppen Geiger classifications, Egypt has two climatic zones, BWh and BSh [157–159]. BWh climatic zones belong to hot desert environments, whereas BSh climate zones belong to hot semi-arid environments. Despite this, the ASHRAE classifies Egypt into Very Hot-Dry (1B), Hot-Dry (2B), and Hot-Humid (2A) climate regions [160]. Aswan, Cairo, and Alexandria have been chosen as typical representative cities for each climatic region.

To quantify the energy needs of a building placed in these three locations, the Degree Day methodology is used. This method estimates the heating needs (HDD or Heating Degree Days) and cooling needs (CDD or Cooling Degree Days) based on the external conditions and energy requirements of the building necessary to achieve a comfortable -indoor environment [161,162]. The calculations have been made to establish setpoint temperatures for heating and cooling 15 ºC and 18 ºC, respectively [163].

The latest recently cooling degree days (CDD) and heating degree days (HDD) statistics, as well as the most recent suggested annual design parameters and average wind speed, are shown in Table (3-3), with the yearly Direct Normal Irradiation (DNI) for the three representative cities.

Table 3-3: Cities recommended design conditions [160,161,164–166]

Location	Cooling Degree Days	Heating Degree Days	ASHRAE Climate Zone	Dry-Bulb Temperature (ºC)	Wet-Bulb Temperature (ºC)	Direct Normal Irradiation (kWh/m^2)	Wind Speed (m/s)
Aswan	6564.1	131.2	1B	44.1	21.1	2254	4.04
Cairo	4861.7	150.3	2B	38.2	21.2	2036	3.58
Alexandria	3739.9	192.1	2A	33.2	22.4	1955	3.92

3.6 Envelope Characteristics

The facilities management office provided the required as-built info for the baseline model development. The wall area is 3473 m^2, and the rooftop area is approximately 1913 m^2. The building envelope materials have nearly identical values to those employed in most non-residential structures in the Egyptian market, as represented in Table (3-4).

Table 3-4: Building envelope characteristics

External Wall	
U-factor (W/ m^2 °C)	1.924
Roof	
U-factor (W/ m^2 °C)	2.27
Windows	
Average Window Fraction (Window-to-Wall Ratio)	30%
Glazing	6 mm Double Blue Glass/ 6mm Air Gap
U-factor (W/ m^2 °C)	3.094
SHGC	0.503

3.7 Internal Loads

Internal heat gains include those produced by humans, lights, electrical appliances, and miscellaneous equipment placed within the property.

3.7.1 Occupant Density

The occupant load density is defined as the ratio of its total floor area to its total number of occupants. The ratios for occupancy density per space type were defined in accordance with ASHRAE [167] and are represented in Table (3-5).

Table 3-5: Recommended occupant densities for institutional buildings

Zone	Occupant Density (#/100 m^2)
Classroom	65
Coffee Stations	20
Computer lab	25
Conference/Meeting	50
Corridors	-
Laboratories	25
Lecture hall	150
Libraries	10
Lounge	50
Main entry lobbies	10
Office Spaces	5
Reception Areas	30
Restaurants	70

3.7.2 Interior Lighting

Most international codes and global standards specify Lighting Power Density (LPD) as the lighting power requirement. When measuring LPD, watts per square meter (W/m^2) is used. The LPD in this analysis is set as in Table (3-6) according to ASHRAE [168] using the space-by-space method.

Table 3-6: Recommended LPD for institutional buildings

Zone	LPD (W/m^2)
Classroom	13.4
Coffee Stations	7
Computer lab	18.4
Conference/Meeting	13.3
Corridors	9.9
Laboratories	15.5
Lecture hall	13.4
Libraries	11.5
Lounge	7.9
Main entry lobbies	9.7
Office Spaces	12
Reception Areas	5.9
Restaurants	11.6

3.7.3 Plug and Process Loads

This type of electrical load is not connected to lighting, heating, or air conditioning and often does not offer comfort for the occupants [168]. Plug and process loads (PPL) are the amount of energy consumed by equipment that is commonly connected to an electrical outlet, such as office and general miscellaneous appliances, workstations, and other devices that are toughly quantified. PPL densities tabulated in Table (3-7) are per by ASHRAE [160,169].

Table 3-7: Recommended PPL densities for institutional buildings

Zone	PPL (W/m^2)
Classroom	4.7
Coffee Stations	18.54
Computer lab	21.5
Conference/Meeting	9.38
Corridors	2
Laboratories	10.95
Lecture hall	2
Libraries	13.3
Lounge	2.12
Main entry lobbies	2.5
Office Spaces	11.99
Reception Areas	5.59
Restaurants	66.74

3.8 Ventilation Requirement

ASHRAE defines Ventilation as "the process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space." The recommended ventilation rates for educational buildings are tabulated in Table (3-8) as per ASHRAE standards [167].

Table 3-8: Recommended ventilation rates for institutional buildings

Zone	Ventilation rate (L/s-person)	Ventilation rate (L/s-m^2)
Classroom	3.8	0.3
Coffee Stations	2.5	0.3
Computer lab	5	0.6
Conference/Meeting	2.5	0.3
Corridors	-	0.3
Laboratories	5	0.9
Lecture hall	3.8	0.3
Libraries	2.5	0.6
Lounge	2.5	0.6
Main entry lobbies	2.5	0.3
Office Spaces	2.5	0.3
Reception Areas	2.5	0.3
Restaurants	3.8	0.9

3.9 Baseline Model Validation

Once the baseline model of the building has been developed, it is necessary to verify the fidelity of its results. To be meaningful, the model needs to be liable for forecasting the system's behavior while considering the vital factors impacting the system. Developing energy models, which can be relied upon to help achieve a healthier, sustainable energy future, requires ensuring the simulations' validity. The validation process is based on comparisons between the predictions of the theoretical model and the experimental measurements. These procedures allow quantifying the mismatches and deviations obtained between the new model and the experimental values. For this purpose, a pair of methodologies suggested by the National Renewable Energy Laboratory (NREL) was employed to verify and validate the built-up model [170]. As shown in Figure (3-7), the annual baseline model Energy Use Intensity (EUI in kWh/m^2), predicted by the simulation tool, was initially comparable to that of other institutions in hot environments.

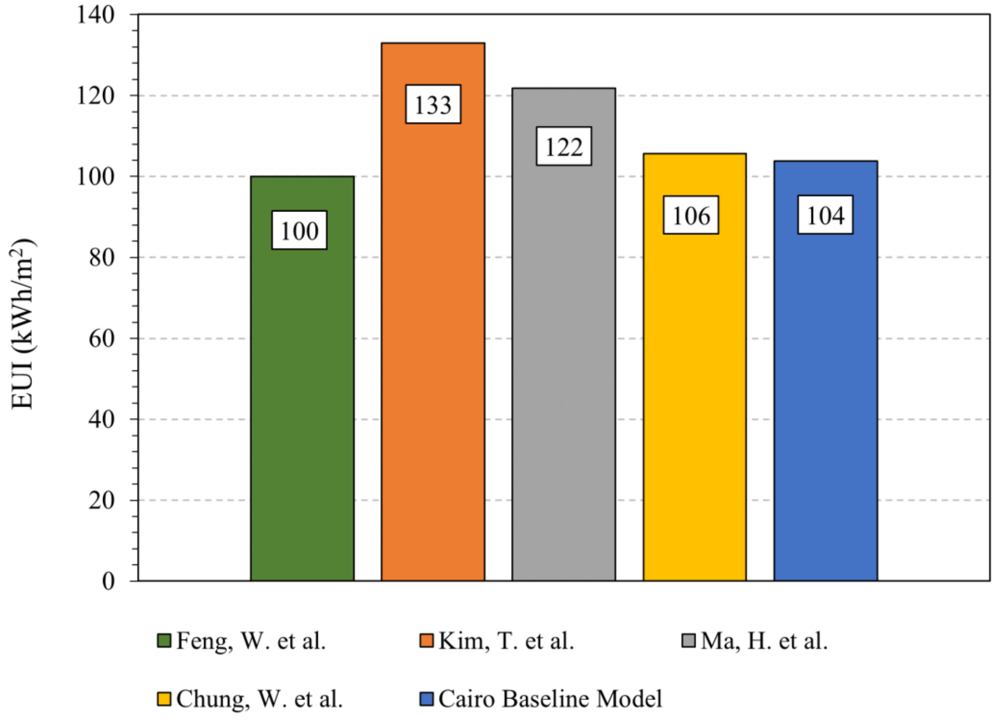

Figure 3-7: The EUI of the baseline model of Cairo compared to other studies [171–174]

There are various advantages to conducting a comparative study. It does not necessitate collecting data from the actual facility; furthermore, it indicates whether additional investigation is necessary. Given the absence of the reality model, the comparative method performs effectively when combined with other validation procedures.

To ensure the validity of building energy predictions, models are contrasted to actual real data. The second procedure relies on testing the model EUI against data from the Building Management System (BMS) collected on-site. The validation graph is illustrated in Figure (3-8). As prescribed by the ASHRAE guideline 14:2015, two indicators were computed to demonstrate the representativeness of the modeling depending on the variability of the observed data: Normalized mean bias error (NMBE), additionally to the Coefficient of variation of the root, mean square error (CVRMSE) [175]. According to this guide, the value must be less than ±10% for the NMBE coefficient and less than 30% for the CVRMSE coefficient. The NMBE for the baseline model is estimated to be 6%, whereas the CVRMSE is nearly 3%.

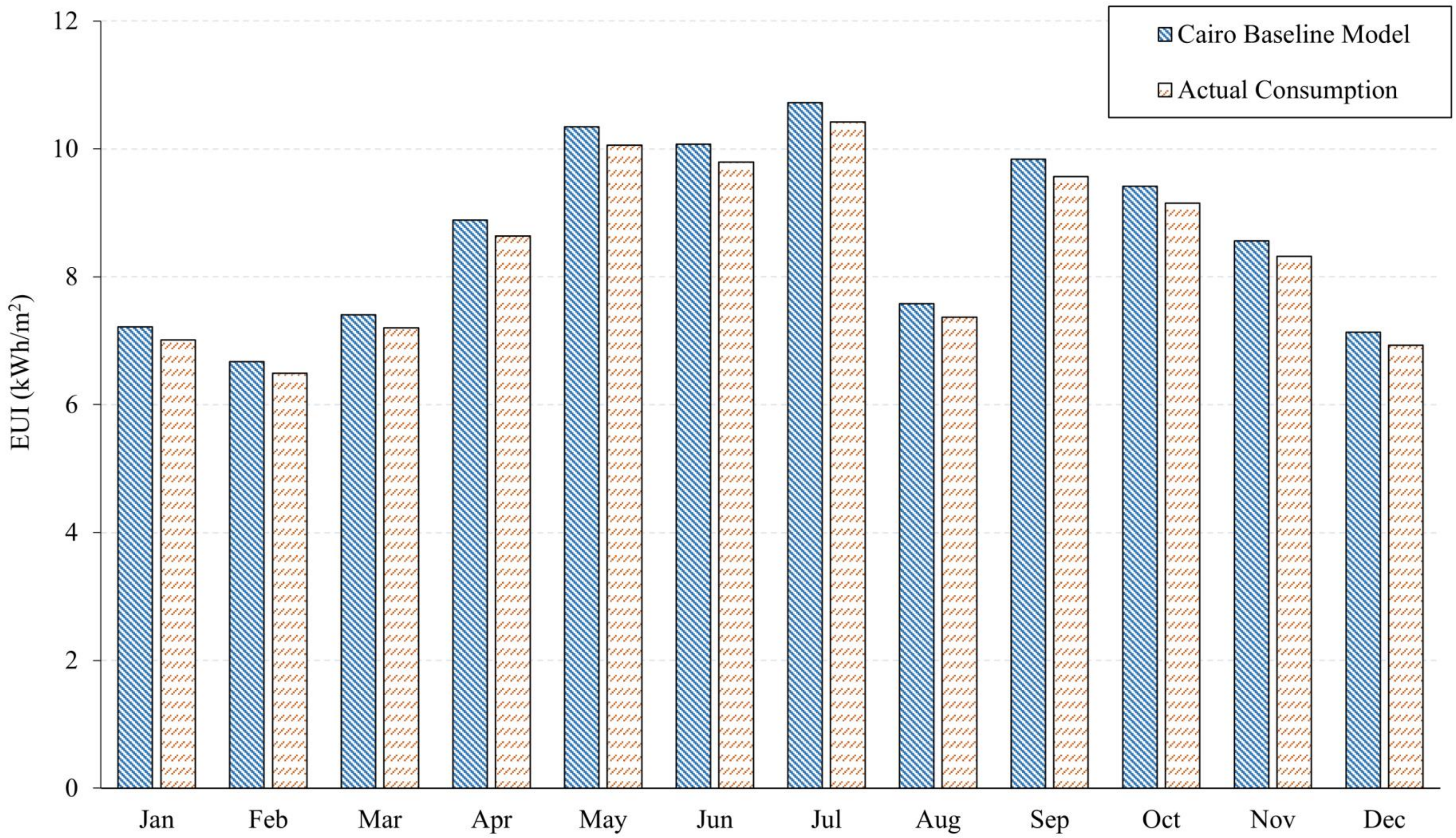

Figure 3-8: Baseline model validation, Cairo, Egypt

3.10 Energy Analysis Methodology

The optimal performance of a building has to fulfill minimal energy and cost requirements based on the thermal properties of the envelope, windows renovation, operational characteristics, use of renewable technologies or heating, ventilation and air conditioning systems. Therefore, it is necessary to identify the influence of each measure proposed as a function of the boundary conditions in order to select the most appropriate ones for the three studied climatic zones. In this work, an energy analysis methodology has been applied with the final goal of proposing an optimized building configuration based on energy savings, cost, carbon emissions, and thermal comfort levels. With this aim, the following phases have been implemented:

- Identification of the main rehabilitation measures based on the building energy utilization.
- Selection of the most influential rehabilitation measures through local sensitivity analysis.
- Quantification the influence of each measure on energy consumption and thermal comfort for each climatic zone.
- Creation of the decision matrix weighing the evaluation criteria.
- Selection of an optimized building configuration.
- Comparative between the upgraded and base building configuration.

A first selection of the studied measured in the building performance has been done through the assessment of the energy utilization. This study is carried out in the baseline model by determining the ratio of the component to the entire energy consumption of the facility. Figure (3-9) represents the energy utilization curves obtained for the building located in Cairo, Egypt.

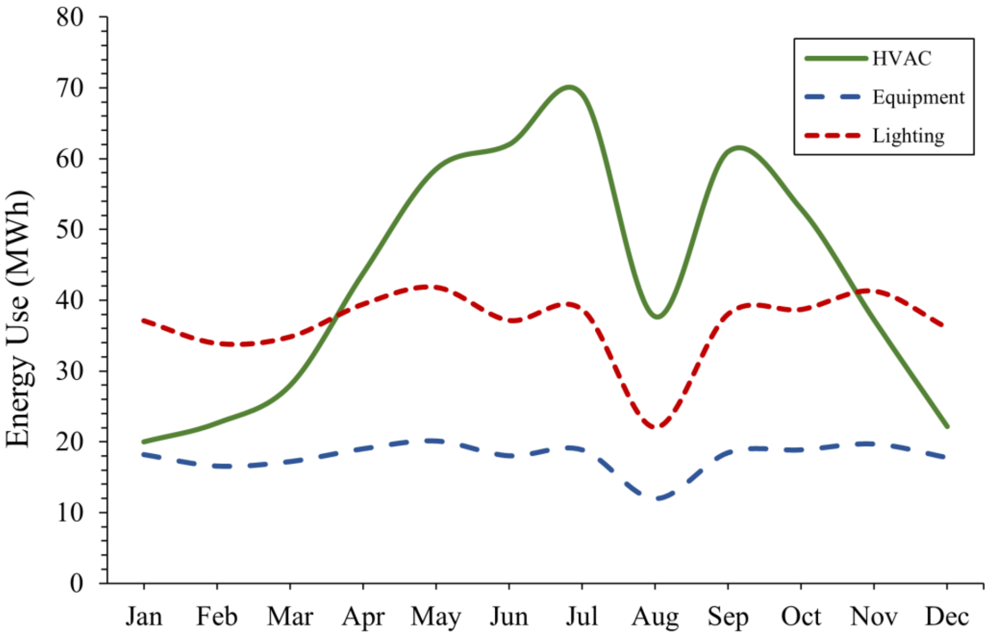

Figure 3-9: Energy breakdown of Cairo baseline model

HVAC systems compromise nearly half of the facility's overall energy cost, consistent with previous studies [7,12,13,97,98,174]. It is noticeable that HVAC energy utilization dramatically increases during the summer season as a direct product of hot summer conditions. The lighting and equipment energy use remain nearly the same throughout the year with ratios of 35% and 20%, respectively, except in August. This decrease in building energy use during August is linked to the annual and summer vacations. Based on the results of this first approximation, the following retrofit measures are proposed to be evaluated in the sensitivity analysis:

- Building envelope.
- Conditioning systems.
- Lighting devices.
- Occupant’s behavior.

Secondly, a sensitivity analysis is carried out to quantify the influence of the proposed measures highlighted by the energy utilization of the building in Cairo. There is a wide variety of sensitivity analysis that allows quantifying the influence of the proposed measures: local and global [154–156]. Local sensitivity analysis varies only one design parameter while the rest remain constant. Global sensitivity analysis is used to study the coupled impact of the proposed measures, studying the entire inlet space of variables. Through the use of energy models as well as empirical analysis, it is possible to reveal the most significant factors affecting a building's thermal performance [153]. In this work, a local sensitivity analysis has been selected based on the easiness of implementing the results in a decision matrix, low computational cost and easy visualization of the information produced. However, it must be taken into account that this procedure presents some limitations in the results obtained, since it does not analyze the cumulative impacts produced by the combination of measures.

Once the influential measures have been identified through a sensitivity analysis, a study of each one has been carried out to quantify their influence on energy consumption and thermal comfort. This study has considered technical, environmental, and economic aspects as evaluation criteria or cost functions. These factors have been weighted to create a multi-objective matrix that makes it possible to identify solutions that enable decision-making process based on the evaluation criteria. Finally, an integrated model is proposed that combines different rehabilitation measures, comparing the energy performance of this upgraded solution with the base model.

4. RESULTS DISCUSSION AND ANALYSIS

In the context of the energy economy, achieving energy efficiency in zones where cooling requirements in buildings surpass heating needs is critical. Extra studies centering on indoor environmental quality associated with the execution of proposed solutions must arise in such regions in tandem with the energy economy development of the country.

The findings of various influences employed for energy efficiency will be discussed in this chapter to analyze the influence of each parameter on energy performance. The influence of each parameter on energy consumption, CO_2 emissions, and resulting thermal comfort was examined in detail. The results in this section have been reformatted from the original published versions for inclusion in the dissertation.

Once the baseline building has been modeled and validated (chapter 3), the influence exerted by different rehabilitation measures on the energy performance as well as the selection of a proposed integrated solution is quantified. These evaluations are done based on the energy analysis methodology proposed in chapter 3 and shown in Figure (4-1).

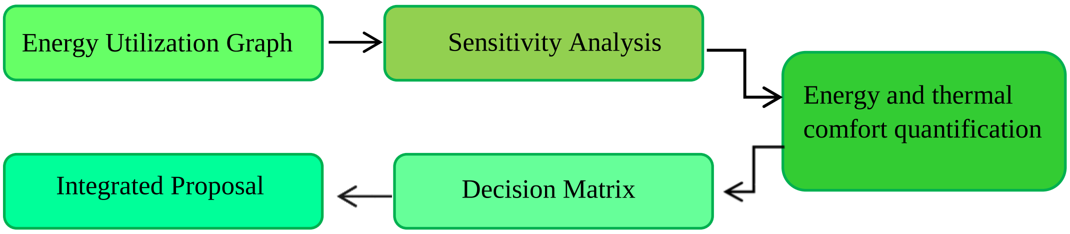

Figure 4-1: Energy analysis methodology scheme defined in chapter 3

Based on this methodology, different options to optimize the building retrofit measures are highlighted by the energy utilization graph. With these inputs, four measured are selected to be evaluated through a sensitivity analysis: building envelope, conditioning systems, lighting devices and occupant behavior. This chapter highlights the great influence exerted by the building envelope and HVAC systems on the energy performance of the building. These measures are assessed to quantify their influence on energy consumption and thermal comfort, weighing each option technically, environmental, and economically. This procedure is given rise to a multi-objective matrix that allows a decision-making process using technical, environmental, and economic criteria. Finally, an integrated model is proposed whose building performance is compared with the baseline model.

4.1 Sensitivity Analysis

The influence on the energy performance exerted by the retrofit measures previously proposed in chapter 3 has been evaluated with a local sensitivity analysis. This procedure identifies the most influential strategies using parametric simulations, modifying only one parameter of the baseline validated model while the rest are kept constant.

Figure (4-2) shows the fraction of the parameters influencing the building heat gains that affect energy consumption.

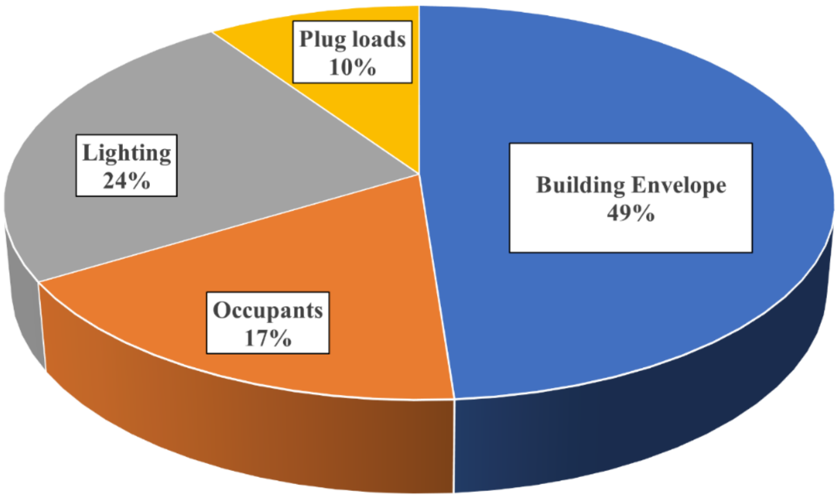

Figure 4-2: Sensitivity analysis of the validated baseline model

This sensitivity analysis reveals that the building envelope accounts for almost half of the overall heat gain in a building, which byproducts heavily affect energy consumption, particularly HVAC energy use. Depending on this finding, this study intends to explore the efficiency of various building envelope solutions and HVAC systems in Egypt's various hot climatic zones. Based on these results, two groups of measures to optimize the building performance are deeply studied:

- Modification of the building envelope.
- Different types of HVAC systems.

4.2 Building Envelope

In hot regions, such as Egypt, the thermal behavior of the building envelope is critical in both morning and afternoon, when there is a substantial quantity of solar energy. Due to the country's large geography and variety of climates, ASHRAE has categorized Egypt into three different climatic zones: very hot-dry (1B), hot-dry (2B), and hot-humid (2A) climate regions [160].

As mentioned previously, the baseline model sensitivity analysis disclosed that 50% of the heat gain is related to the building envelope. Also, the energy analysis revealed that the HVAC system is responsible for approximately 45% of the total energy consumption, proportional to HVAC energy utilization in several studies in corresponding climates [7,12,13,22,59,97–99].

Two packages of rehabilitation measures have been analyzed on the building envelope, assessing its energy performance, the influence on thermal comfort and its economic performance:

- Thermal insulation.
- Building integrated photovoltaic (BIPV)

4.2.1 Thermal Insulation

This investigation evaluates the behavior of a building in several climate regions, assuming that all other architectural and physical attributes of the building are identical save for the insulative material. The samples under examination are locally available in Egypt, such as Extruded Polystyrene (XPS), Polyurethane (PU), Glass-wool (GW), and imported, such as Reflective Paint (RP). The findings of projected upgrades are assessed and analyzed in terms of the building's annual performance. Keeping this aim in mind, an enviro-economic analysis is conducted to recognize the energy and environmental impact improvements, as well as the consequent thermal comfort, based on the application.

4.2.1.1 Building Energy Response

This subsection assesses the response of the building to the installation of various insulators and thicknesses across the three cities under investigation. The simulations are performed on conventional insulation materials in Egypt, followed by the execution of reflective paint insulating material. The simulations demonstrated that building performance varies by location in Egypt, emanated by the outdoor conditions. To quantify the building energy efficiency obtained in the three locations studied, the indicator Energy Use Intensity (EUI) is used [176]. This energy indicator is calculated using the baseline model, running simulations that keep constant with all parameters being constant except the weather conditions as Table (4-1) illustrates.

Table 4-1: Baseline model energy consumption in tested locations

Model	**Baseline Building Model**		
	Aswan, Egypt	**Cairo, Egypt**	**Alexandria, Egypt**
Cooling Degree Days	6564.1	4861.7	3739.9
Heating Degree Days	131.2	150.3	192.1
Whole Building Energy Use (GWh)	1.311	1.178	1.091

The energy demands are higher in locations with hotter climates, such as Aswan (Zone 1B), followed by Cairo (Zone 2B), and Alexandria (Zone 2A), as Table (4-1) shows.

Following the baseline models, the implementation of different insulation materials has been tested in terms of whole-building energy consumption as well as the HVAC energy use for the three climates. Masonry/insulation/masonry construction are preferable for cooling dominant regions [17,177].

Table (4-2) shows the thermal insulation materials effect on both whole-building energy use and HVAC energy utilization in Aswan. The outcomes are graphically illustrated in Figure (4-3). The tests demonstrate that reflective paints, driven by Egypt's high solar intensity, have the lowest whole-building energy use and HVAC utilization. At the same time, 25 mm PU is the least effective implementation among tested materials.

Table 4-2: Energy response of insulating materials and their thicknesses, Aswan

Model	Aswan, Egypt	
	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)
Baseline	1.311	0.654
25 mm PU	1.152	0.498
25 mm XPS	1.142	0.488
25 mm GW	1.149	0.496
50 mm PU	1.120	0.466
50 mm XPS	1.111	0.458
50 mm GW	1.117	0.464
75 mm PU	1.105	0.451
75 mm XPS	1.096	0.443
75 mm GW	1.102	0.448
100 mm PU	1.098	0.444
100 mm XPS	1.087	0.434
100 mm GW	1.093	0.439
Reflective Paint	1.041	0.383

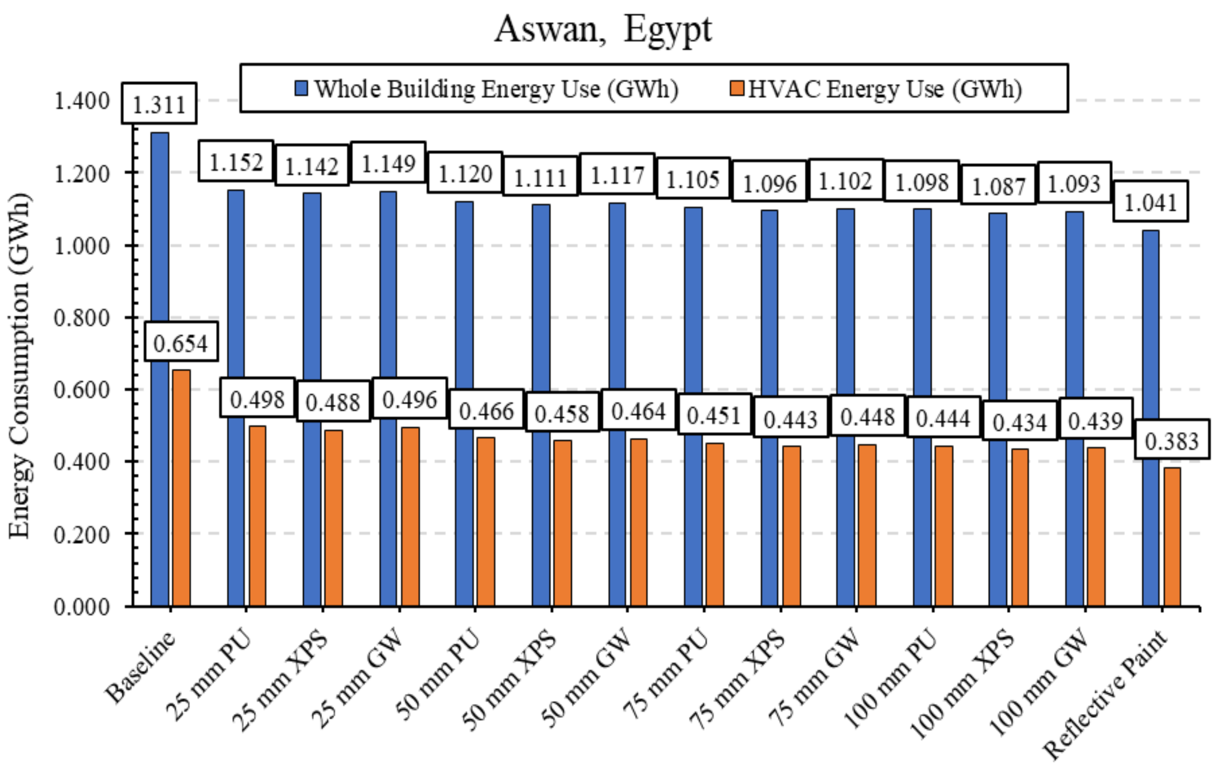

Figure 4-3: Energy response simulation outcomes of insulation materials in Aswan

For the hot-arid zone 2B, Cairo's representative city has been tested. Table (4-3) reflects the impact of the thermal insulation materials upon both whole-building energy use and HVAC energy utilization in Cairo. The experiments reveal that reflective paints have the lowest total building energy consumption and HVAC use, whereas 25 mm PU has the least efficient implementation among the studied materials.

Table 4-3: Energy response of insulating materials and their thicknesses, Cairo

Model	**Cairo, Egypt**	
	Whole Building Energy Use (GWh)	**HVAC Energy Use (GWh)**
Baseline	1.178	0.520
25 mm PU	1.093	0.439
25 mm XPS	1.083	0.429
25 mm GW	1.087	0.434
50 mm PU	1.077	0.423
50 mm XPS	1.069	0.416
50 mm GW	1.073	0.420
75 mm PU	1.069	0.415
75 mm XPS	1.063	0.409
75 mm GW	1.065	0.411
100 mm PU	1.068	0.415
100 mm XPS	1.059	0.405
100 mm GW	1.061	0.407
Reflective Paint	0.949	0.295

Moreover, the simulation outcomes are graphically illustrated, as shown in Figure (4-4).

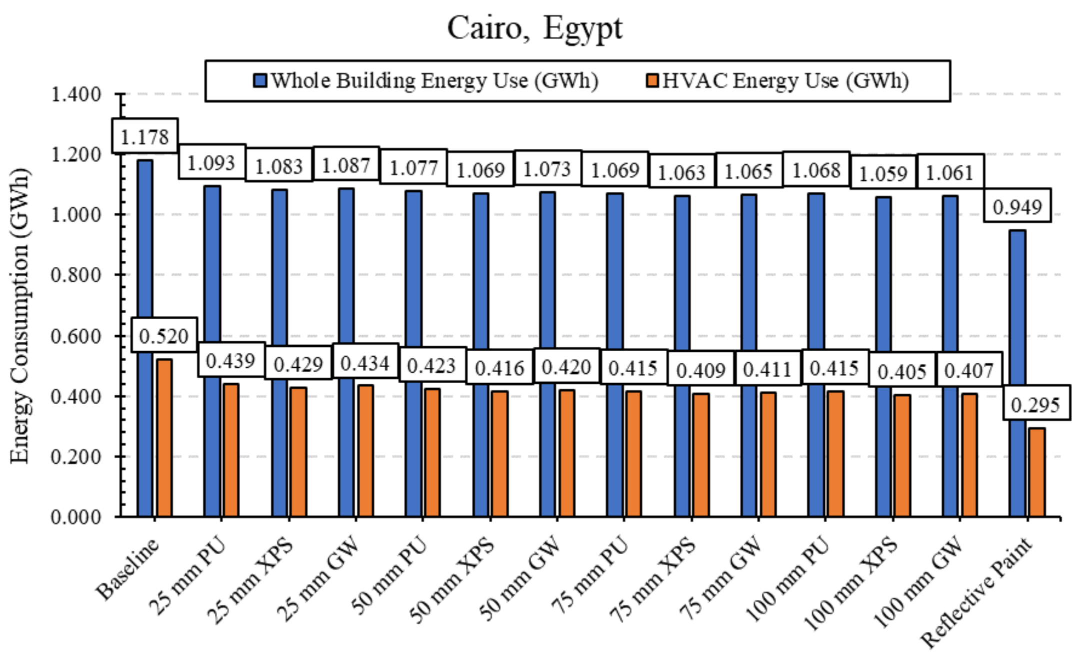

Figure 4-4: Energy response simulation outcomes of insulation materials in Cairo

The investigation has been expanded to include zone 2A, represented by Alexandria city. The findings are tabulated in Table (4-4) while graphed in Figure (4-5). Experiments show that reflective paints require less energy than any other material investigated, whereas 25 mm PU is the least efficient among the examined materials.

Table 4-4: Energy response of insulating materials and their thicknesses, Alexandria

Model	**Alexandria, Egypt**	
	Whole Building Energy Use (GWh)	**HVAC Energy Use (GWh)**
Baseline	1.091	0.431
25 mm PU	1.043	0.389
25 mm XPS	1.034	0.381
25 mm GW	1.036	0.383
50 mm PU	1.039	0.385
50 mm XPS	1.029	0.375
50 mm GW	1.031	0.377
75 mm PU	1.036	0.382
75 mm XPS	1.027	0.374
75 mm GW	1.028	0.374
100 mm PU	1.035	0.381
100 mm XPS	1.027	0.373
100 mm GW	1.026	0.373
Reflective Paint	0.905	0.246

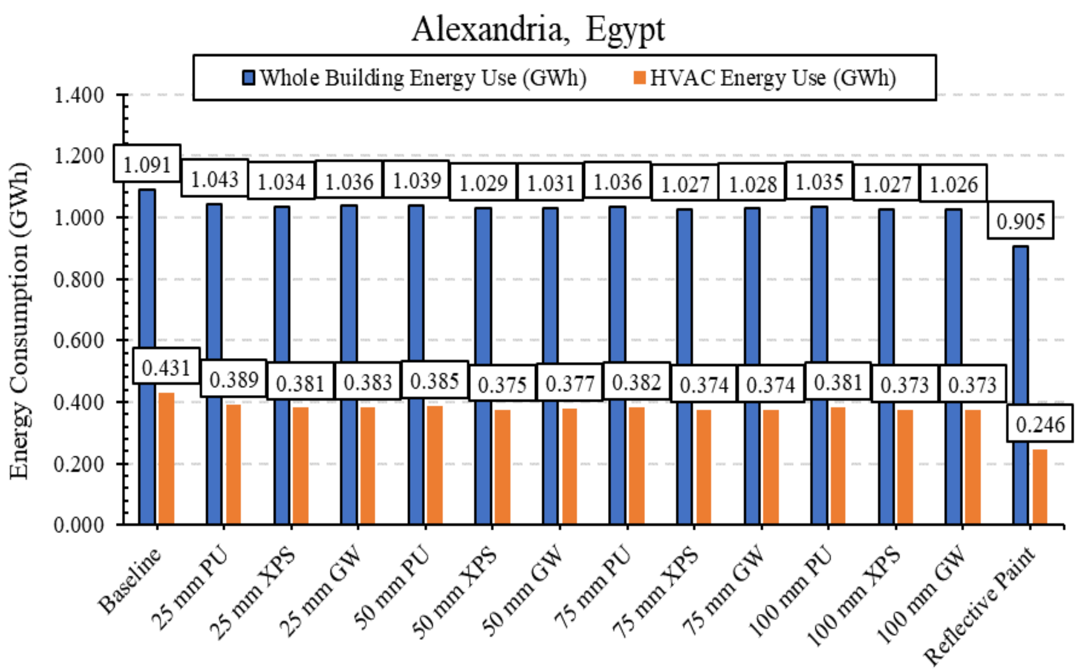

Figure 4-5: Energy response simulation outcomes of insulation materials in Alexandria

As presumed, increasing insulating thickness results in increased energy reductions; however, the trend is logarithmic. The increase in insulation thickness is compared in the three locations, as illustrated in Figure (4-6).

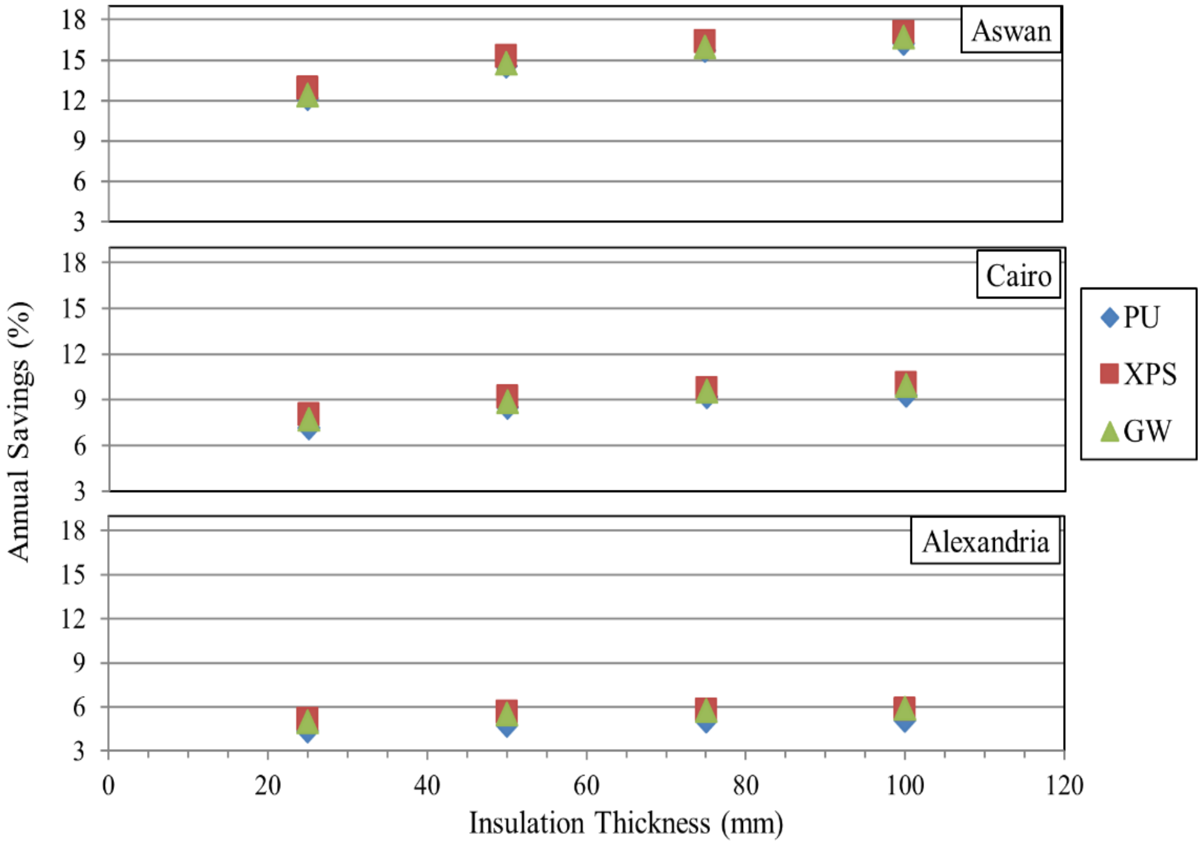

Figure 4-6: Logarithmic trend of insulation materials in the three locations

According to the EUI indicator, the amount of energy a building consumes is calculated as a function of the size and/or features. EUI is defined in terms of the building's annual energy use per unit area. The EUI is a valuable factor when benchmarking or comparing buildings' performance to others [178]. Bearing this in mind, the EUI for all models has been estimated as presented in Table (4-5).

Table 4-5: Estimated building EUI for thermal insulation models for the three locations

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	EUI (kWh/m^2)		
Baseline	115.6	103.8	96.1
25 mm PU	101.5	96.3	91.9
25 mm XPS	100.6	95.4	91.1
25 mm GW	101.2	95.8	91.3
50 mm PU	98.7	94.9	91.5
50 mm XPS	97.9	94.2	90.6
50 mm GW	98.5	94.6	90.8
75 mm PU	97.4	94.2	91.2
75 mm XPS	96.6	93.7	90.5
75 mm GW	97.1	93.8	90.6
100 mm PU	96.8	94.1	91.2
100 mm XPS	95.8	93.3	90.5
100 mm GW	96.3	93.5	90.4
Reflective Paint	91.7	83.6	79.8

The response of the building energy performance in terms of EUI for all tested insulators has been visualized in Figure (4-7) for the three climatic zones under investigation. As can be seen, the highest percentages of energy savings are always achieved in Aswan, followed by Cairo and Alexandria with the lowest percentages. Since Aswan is located in a very-hot region with the highest solar energy density and outdoor conditions, energy savings are always the greatest.

Using the reflective paints, Aswan, Cairo, and Alexandria sustained immense proportions of energy savings (21%, 19%, and 17%, respectively), succeeded by XPS (highest reductions for Aswan, Cairo, and Alexandria of 17%, 10%, and 6%), GW (highest reductions for Aswan, Cairo, and Alexandria of 17%, 10%, and 6%), and PU (highest reductions for Aswan, Cairo, and Alexandria of 16%, 9%, and 5%).

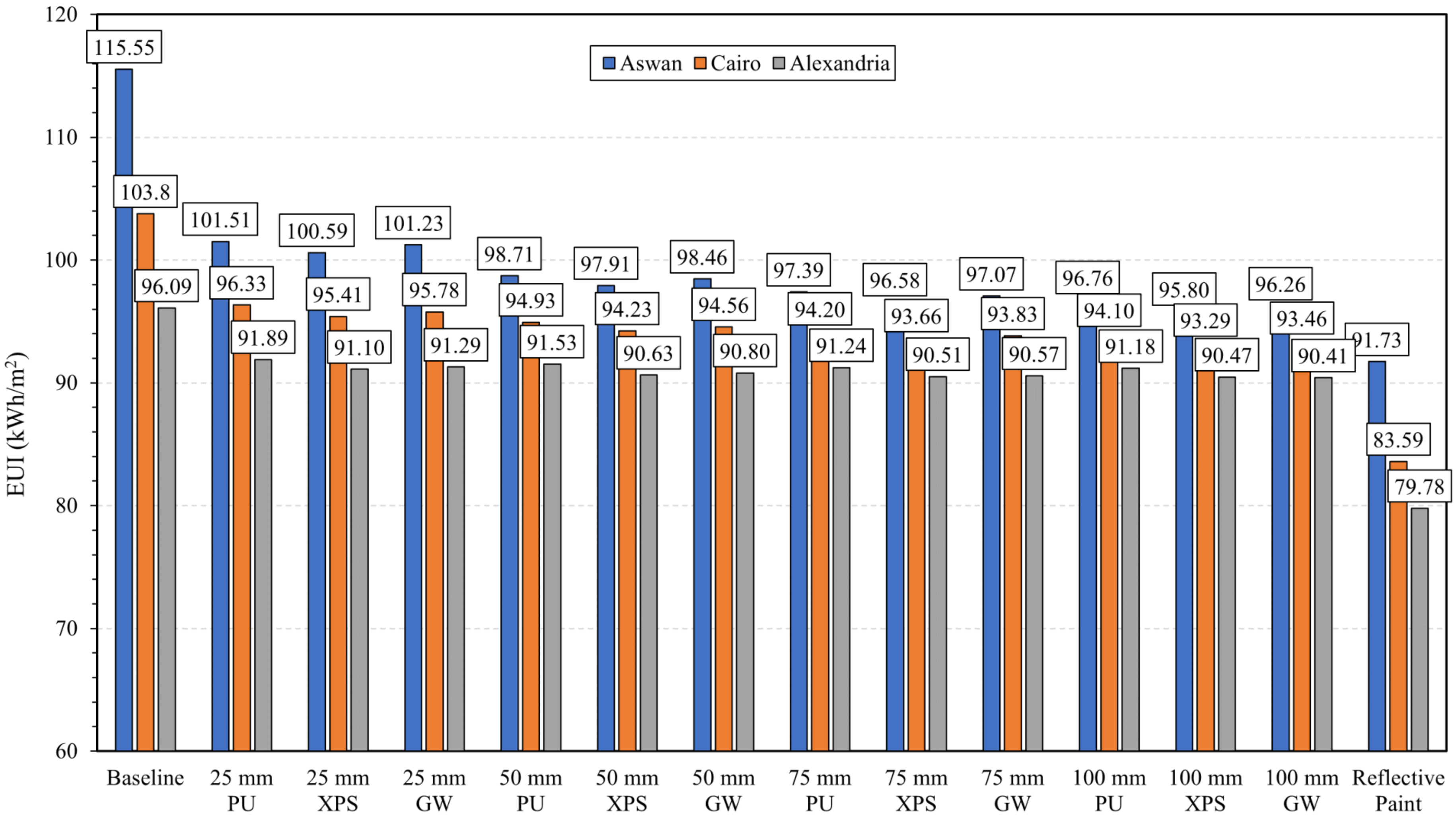

Figure 4-7: EUI response linked to thermal insulators for the three climates

4.2.1.2 Operational Carbon Emission Assessment

Since electric power production and distribution are just nearly 33% efficient, around 3 kWh of overall energy is required for the generation and delivery of 1 kWh to the end-user [58,179]. Thus, cutting energy use reduces carbon emissions and hence protects the environment. Under the Environmental Protection Agency (EPA), 0.0007 tons of CO_2 are released per one kWh of electricity consumption [180].

Considering various insulation thicknesses, Table (4-6) shows Carbon emissions reductions compared to the baseline model at each location.

Table 4-6: Operational CO_2 emission reductions

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	CO_2 Reduction %		
Baseline	-	-	-
25 mm PU	12.2	7.2	4.4
25 mm XPS	12.9	8.1	5.2
25 mm GW	12.4	7.7	5.0
50 mm PU	14.6	8.5	4.8
50 mm XPS	15.3	9.2	5.7
50 mm GW	14.8	8.9	5.5
75 mm PU	15.7	9.2	5.0
75 mm XPS	16.4	9.7	5.8
75 mm GW	16.0	9.6	5.8
100 mm PU	16.3	9.3	5.1
100 mm XPS	17.1	10.1	5.9
100 mm GW	16.7	9.9	5.9
Reflective Paint	20.6	19.5	17.0

The thicker the insulation, the more significant the reduction in carbon emissions. Among assessed materials, reflective paint was the most environmentally friendly solution evaluated, succeeded by XPS, GW, and PU, respectively. In all cases, the highest CO_2 savings take place in Aswan, followed by Cairo and Alexandria.

4.2.1.3 Techno-economic Assessment

A cost assessment relying on both technical and economic methodologies is well-known as techno-economic evaluation. These assessments are useful for a variety of tasks, such as:

- Evaluate the economic feasibility of a specific project.
- Assess investments' lifetime cash balances.
- Examine the viability of alternative technological levels and executions.
- Comparing the cost-effectiveness of several technology systems that perform similar functions.

This investigation takes into consideration Egypt's latest electricity tariff for commercial applications of 1.6 EGP per kWh. Investment in this analysis is equivalent to the price difference among the baseline and alternative models, all of which are subjected to a 10% discount rate. Table (4-7) summarizes the current Egyptian market pricing for insulating and the economic analysis findings for Aswan, Table (4-8) illustrates the findings for Cairo, while Table (4-9) demonstrates the outcomes for Alexandria.

Table 4-7: Thermal insulation techno-economic analysis, Aswan

Model	**EGP/m^2**	**Aswan, Egypt**			
		IRR	**ROI**	**NPV (EGP)**	**PBP (Years)**
25 mm PU	115	41.5%	27.2%	1,062,393	2.2
50 mm PU	200	27.3%	18.8%	942,969	3.2
75 mm PU	283	18.9%	14.3%	651,058	4.2
100 mm PU	358	13.7%	11.7%	322,579	5.2
25 mm XPS	63	81.6%	52.7%	1,452,071	1.1
50 mm XPS	103	59.2%	38.2%	1,560,322	1.6
75 mm XPS	140	46.4%	30.2%	1,518,986	2
100 mm XPS	165	40.7%	26.7%	1,478,102	2.3
25 mm GW	71	69.8%	45.1%	1,334,618	1.3
50 mm GW	119	49.5%	32.1%	1,409,298	1.9
75 mm GW	165	37.9%	24.9%	1,326,297	2.4
100 mm GW	201	31.7%	21.3%	1,226,820	2.8
Reflective Paint	56	145.3%	94.6%	2,552,339	0.6

Table 4-8: Thermal insulation techno-economic analysis, Cairo

Model	EGP/m^2	Cairo, Egypt			
		IRR	ROI	NPV (EGP)	PBP (Years)
25 mm PU	115	19.1%	14.4%	271,514	4.2
50 mm PU	200	9.7%	9.9%	-15,662	6.1
75 mm PU	283	4.0%	7.5%	-377,475	8
100 mm PU	358	-0.2%	6.0%	-770,100	10.1
25 mm XPS	63	45.3%	29.5%	661,780	2.1
50 mm XPS	103	30.6%	20.7%	590,497	2.9
75 mm XPS	140	22.3%	16.1%	457,508	3.8
100 mm XPS	165	18.9%	14.2%	368,154	4.3
25 mm GW	71	38.2%	25.2%	576,458	2.4
50 mm GW	119	24.6%	17.3%	464,863	3.5
75 mm GW	165	17.2%	13.4%	303,074	4.5
100 mm GW	201	13.0%	11.4%	150,513	5.3
Reflective Paint	56	123.4%	80.2%	2,116,179	0.8

Table 4-9: Thermal insulation techno-economic analysis, Alexandria

Model	EGP/m^2	Alexandria, Egypt			
		IRR	ROI	NPV (EGP)	PBP (Years)
25 mm PU	115	5.6%	8.1%	-116,103	7.5
50 mm PU	200	-3.0%	5.1%	527,367	11.9
75 mm PU	283	-7.5%	3.8%	943,366	15.9
100 mm PU	358	-10.6%	3.1%	1,339,990	19.9
25 mm XPS	63	25.1%	17.6%	257,591	3.4
50 mm XPS	103	14.0%	11.8%	101,295	5.1
75 mm XPS	140	7.4%	8.9%	-85,666	6.8
100 mm XPS	165	4.2%	7.6%	-214,294	8
25 mm GW	71	20.5%	15.1%	194,565	4
50 mm GW	119	9.9%	9.9%	-4,241	6.1
75 mm GW	165	3.9%	7.5%	-226,218	8.1
100 mm GW	201	0.6%	6.3%	-404,113	9.7
Reflective Paint	56	100.0%	64.8%	1,652,930	0.9

Notwithstanding the ecological consequence of increasing the thickness of the insulating material, the outcomes demonstrate that adopting 25 mm of XPS is the most cost-effective insulator among the typical insulations examined for Egypt. The outcomes additionally reveal the cost-effectiveness of reflective paints in the three locations among all other insulators. The NPV positive values are always when the ROI is higher than the 10% discount rate, while a negative value is if the indicator is less than this value.

4.2.1.4 Thermal Comfort

If all facility managers agree solely on a single issue, occupant satisfaction is the most frequent operational obstacle they face daily. ASHRAE defines thermal comfort as the "condition of mind that expresses satisfaction with the thermal environment" [181]. This is a relative notion in which one person may perceive hot while another experiences chilly close, possibly switching these claims the following day. Yet a new building may challenge to satisfy the plurality of citizens consistently.

Even though comfort is a remarkably individualized feeling, a set of indicators have been established to emphasize the ideal norms for preserving indoor environments. Two methodologies can be applied to quantify indoor thermal comfort: steady-state and adaptive [182], depending on how these methods solve the energy balance between humans and their surroundings. The regulation of indoor comfort through an analytical methodology improves, improved indoor environmental quality has been reported to enhance productivity to over 25% [183]. However, efficient strategies rarely apply in practice in undeveloped nations, possibly because the knowledge is not broadly understood or recognized. A clear benefit of increasing occupant comfort would be that it reduces claims and complaints and, by-product lowering the operational and maintenance costs. Thermal comfort minimizes operating energy costs when it is supplied effectively. Comfort and energy use of buildings is also linked to numerous design decisions made at various phases of the design process [180]. Thus, with an emphasis on the thermal environment, indoor air quality, and the resources essential to condition citizens and buildings, designers should establish to bridge the building sciences and well-being.

Various elements affect heat storage or release of a material known as thermophysical properties. These properties include the material's thickness (x), thermal conductivity (k), as well as its specific heat capacity (C_p) [184,185]. To clarify the interaction of such components, the correlation among insulating execution (whether dissimilar materials or thicknesses) and thermal comfort, along with entire building energy efficiency, should be demonstrated. Examining and resolving these puzzle bits in a thorough framework always results in a higher, more efficient outcome at an affordable cost.

Considering the steady-state Fanger model [186], this subsection analyses the impact of thermal insulation on indoor thermal comfort. Fanger developed a 7-point scale, known as the predicted mean vote (PMV), to reflect thermal comfort sensation, eventually standardized by the ANSI/ASHRAE 55 and ISO 7730 [181,187]. The PMV index is commonly employed to express comfortability standardized as: (−3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, and +3 hot). The standard ISO 7730 defines PMV levels ranging between -0.5 and +0.5 as comfortable environments [188]. Along with PMV, the discomfort hours (DCH) interpretation employed in work evaluates whether the indoor temperature and humidity level are within the limitations of ASHRAE thermal acceptable ranges or not. The DCH is expressed in hours, simplifying and clarifying its interpretation for non-specialists.

For Aswan, Figure (4-8) depicts the relationship between the obtained PMV with the insulating materials, whereas Cairo is represented by Figure (4-9), and Alexandria is represented by Figure (4-10). As can be seen, in none of the three cities are obtained slightly cool (-1), cool (-2), or cold (-3) indoor environments.

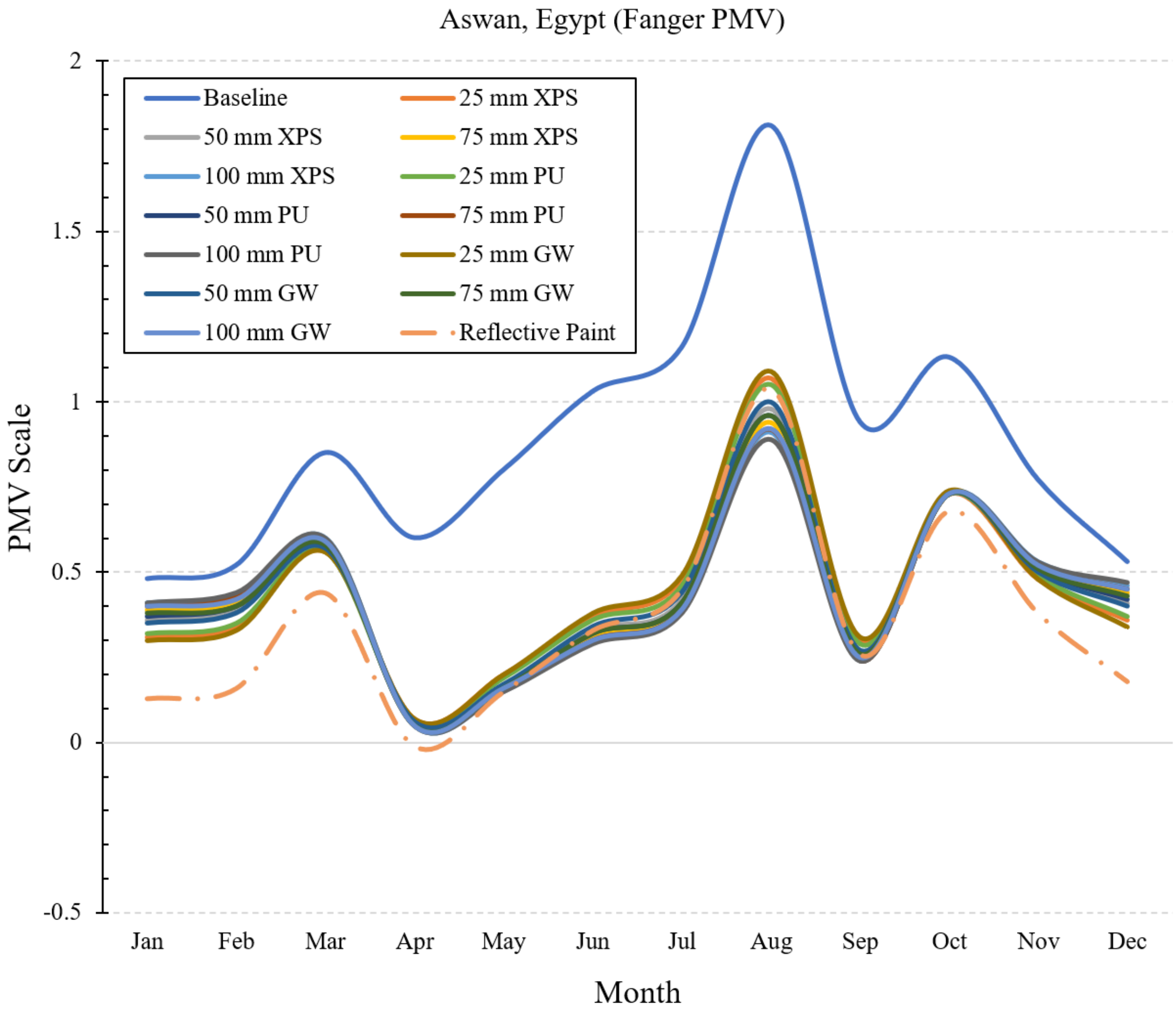

Figure 4-8: PMV-insulation relation, Aswan

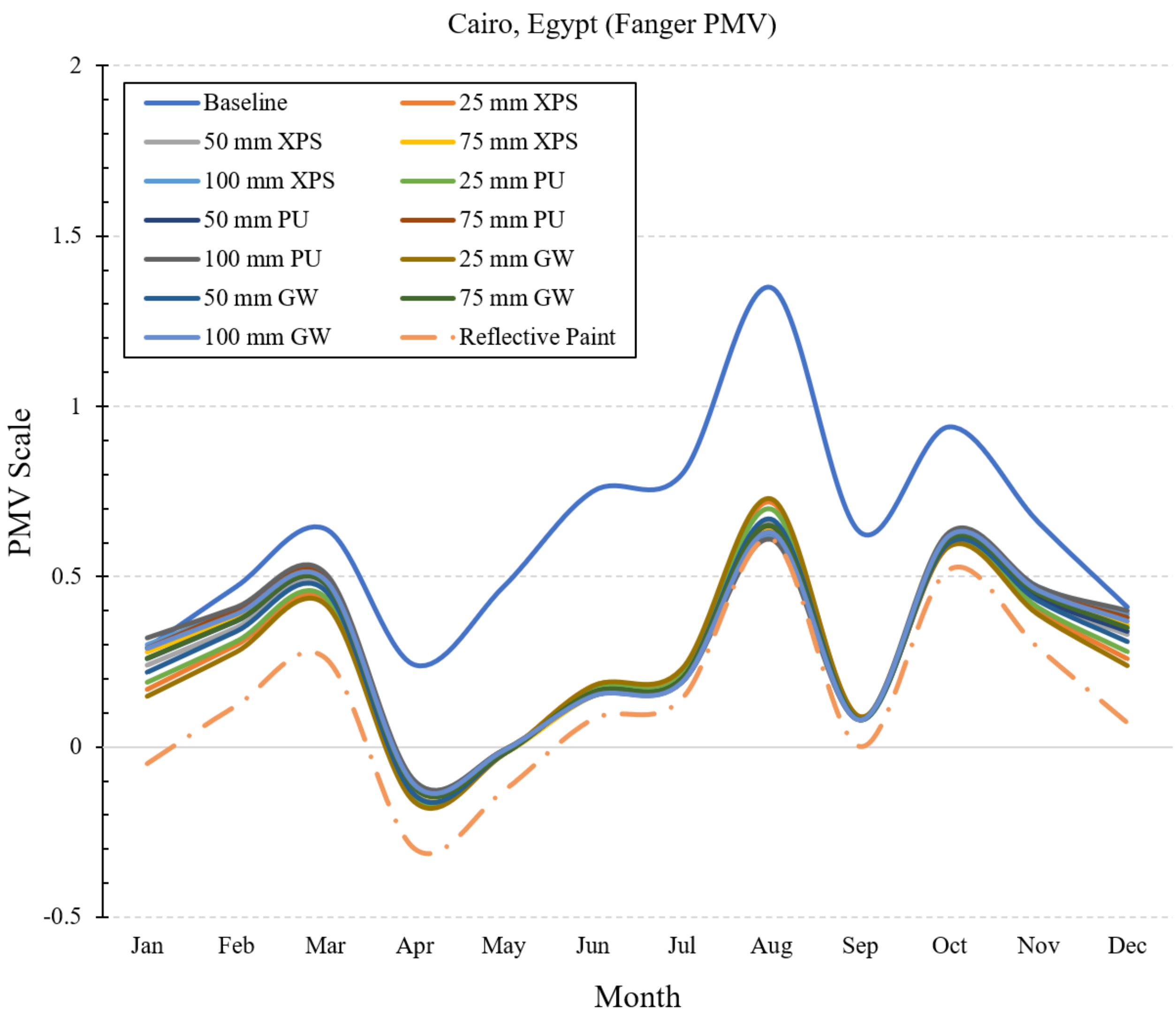

Figure 4-9: PMV-insulation relation, Cairo

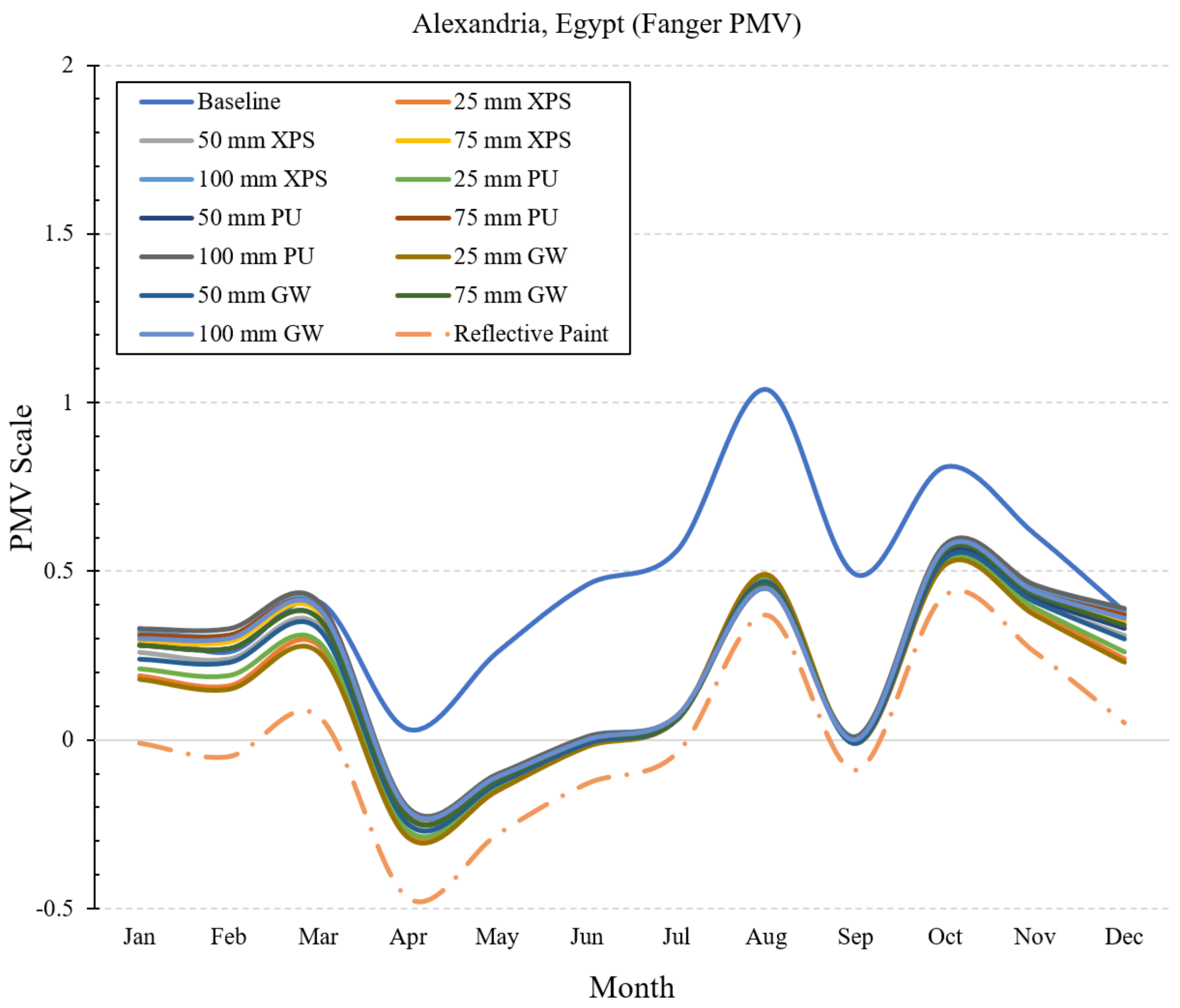

Figure 4-10: PMV-insulation relation, Alexandria

Fanger PMV results for the examined locations are visualized in Figures (4-8), (4-9), and (4-10). Based on the responses of the dynamic models, an enhancement in indoor thermal comfort sensation in the cities of Aswan, Cairo, and Alexandria is directly evident. The models demonstrate that upgrading building envelopes effectively limits the human experience to approximately -0.5 and +0.5 for the majority of the operational time, values within the ranges of thermal comfort accepted by regulations. When the insulation measures on the envelope are taken into account, the highest values of PMV in Aswan and Cairo occur in summer, ranging from slightly warm and warm environments respectively. In Alexandria, the highest PMV values occur between October and November, followed by August, with values close to 0.5. In contrast, the lowest PMV levels when the insulation measures are considered occur in April for the three cities, with values ranging between 0.1 and -0.4.

For simpler indicators, Figure (4-11) relates the different insulating materials under investigation (X-axis) to DCHs (left Y-axis) and the percentage of their reduction for the three climates (right Y-axis). It emphasizes the relevance of insulating material in shrinking indoor thermal discomfort. It clarifies that PMV improvements are directly related to a decrease in the DCH, which byproduct can be used to communicate the benefits to decision-makers and non-specialists and will be used later as an indicator of thermal comfort enhancements. Along with the environmental and economic benefits, the implementation has resulted in a significant reduction in the proportion of the DCH. According to the test, PU insulation with 100 mm thickness lowers DCH by approximately 30%. However, a balanced decision methodology for typical insulators precludes PU owing to its environmental and economic shortcomings. Amongst conventional thermal insulation materials, a balanced solution would be XPS in 25 mm thickness, offering overall ecological, economic, and thermal comfort advantages. Reflective paints, on the other side, should be acquired and used in Egyptian properties due to their significant economic benefit.

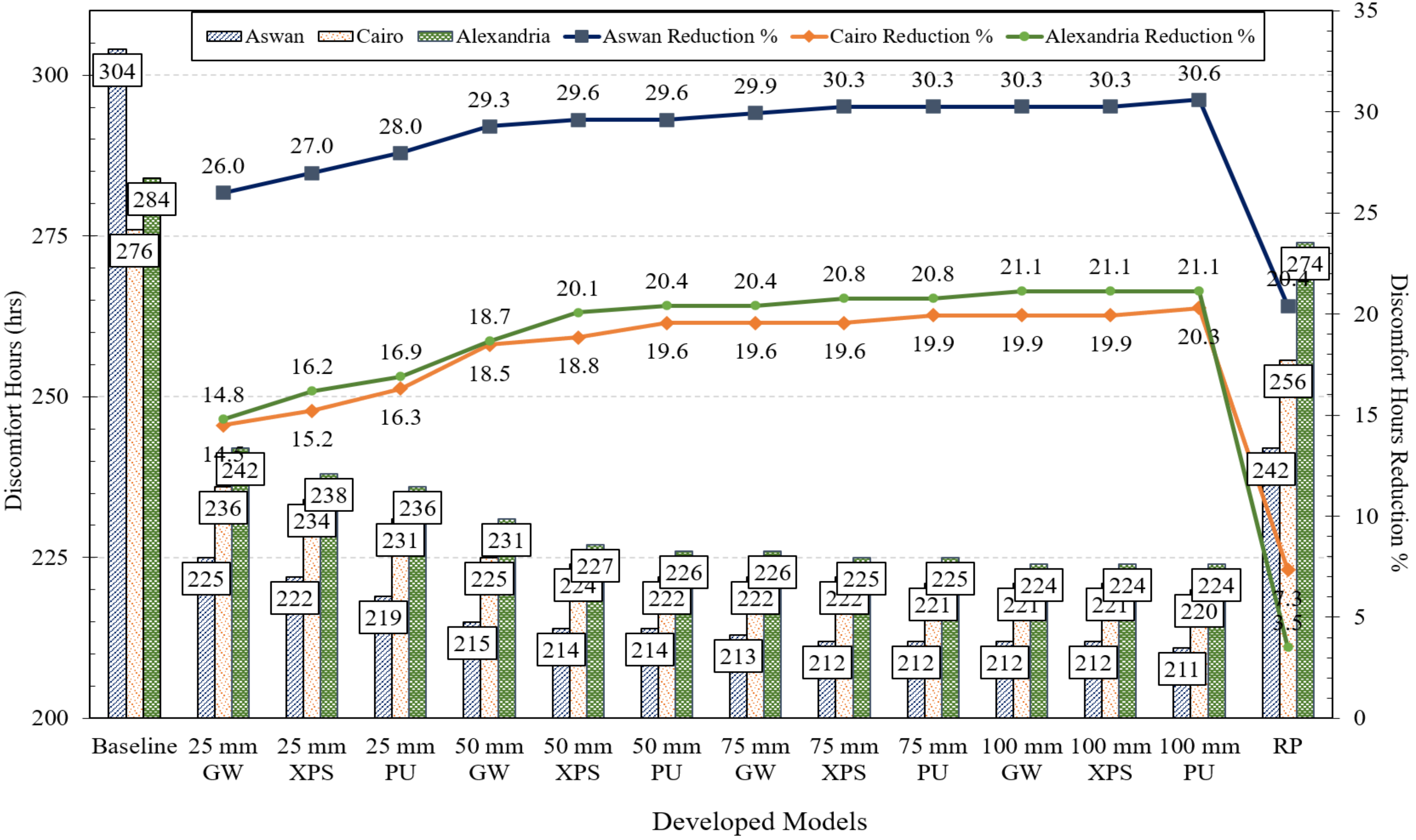

Figure 4-11: Discomfort Hours (DCH)-insulation relation and reduction percentage

4.2.1.5 Proposed Solution and Decision-making

A multi-approach decision strategy is an effective tool for assessing the entire process since it allows the decision-maker to contrast the sustainability of alternative energy-efficient options. The multi-approach decision is a viable strategy for assessing challenging solutions for its capacity to weigh several alternatives involving diverse aspects for the identification of a suitable solution.

The weighing of sustainable criteria has been calculated using two strategies: 1) equalizing the weighting of all factors and 2) granting each factor a specific weight [189]. This analysis is subjected to a weighting approach that allows for optimizing the overall performance of buildings. Three cost functions were considered in the study's weighing approach: 1) economic evaluation, 2) environmental consequences, and 3) indoor thermal comfort. The perspectives of property owners, professionals, and consultants were polled regarding the weighted percentage of each function. Thermal comfort received 45% of the vote, followed by economic benefit at 35% and ecological impact at 20%. The weighting procedure is applied accordingly in the decision-making matrix, and the results are depicted visually in Figure (4-12). According to the findings, reflective paint is the optimum solution derived from the highest economic revenue.

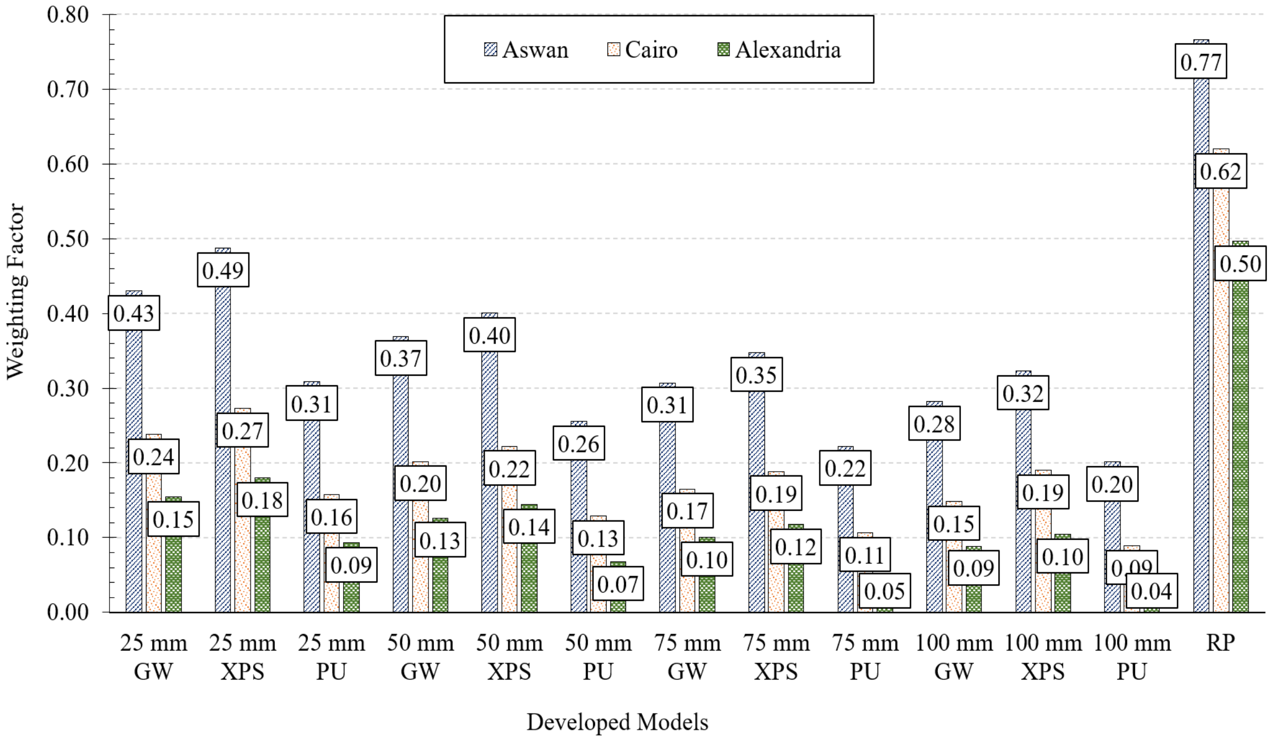

Figure 4-12: Decision-making weighted matrix

4.2.2 Building Integrated Photovoltaics (BIPV)

Construction practices in developing nations are still insufficient to achieve zero-energy buildings. Furthermore, HVAC solutions in non-residential properties utilize most of the facility's energy to maintain thermal comfort levels. For this, a considerable portion of the roof areas are devoted to huge machinery and components [190].

Bearing this in mind, after an enviro-economic evaluation, a solution for the building façade with photovoltaics integration is proposed, whereby it improves building efficiency by decreasing energy consumption while producing clean energy without jeopardizing thermal comfort indoors.

Given there is not enough roofing space for solar panels, this prototype investigates the application of glazing-integrated photovoltaics (GIPV) systems within building envelopes to promote energy efficiency and provide a workable solution for sustainable energy integration [190]. Since daylight can penetrate across BIPV installations, it can alter the ambiance of the interior, relying on the transparency of the BIPV [191]. Owing to GIPV's flexibility and lightweight, it has become simpler to incorporate PV into building components [192].

Since BIPV serve as a component or system of the building envelope, the HVAC system demands of the facility may be directly affected. Thus, any configuration of a BIPV installation should occur concurrently with the building envelope and HVAC systems [193].

Accordingly, the prototype is afterward subjected to the integration with the 25 mm XPS traditional insulators (Ins) and reflecting paints (RP), both of which were recently studied in depth by William et al. [22]. The solutions presented are suitable for both retrofitting and new constructions.

4.2.2.1 Building Energy Response

This subsection assesses the response of the building to the installation of GIPV and its integrations with thermal insulators in the three cities under investigation. The assessment is performed relying on the most current available GIPV specifications and prices [96,194]. The baseline (BL) model is upgraded once by the GIPV only and then tested against the integrated GIPV and insulation (Ins) model, as well as the integrated GIPV and reflective paint (RP) model. The effect of the EUI reductions in the three cities is tabulated in Table (4-10) while graphically illustrated in Figure (4-13).

Table 4-10: EUI related to tested models for the three cities

Model	**Aswan, Egypt**	**Cairo, Egypt**	**Alexandria, Egypt**
	EUI (kWh/m²)		
BL	116	104	96
GIPV + BL	98	93	87
GIPV+ Ins	86	86	83
GIPV + RP	80	73	70

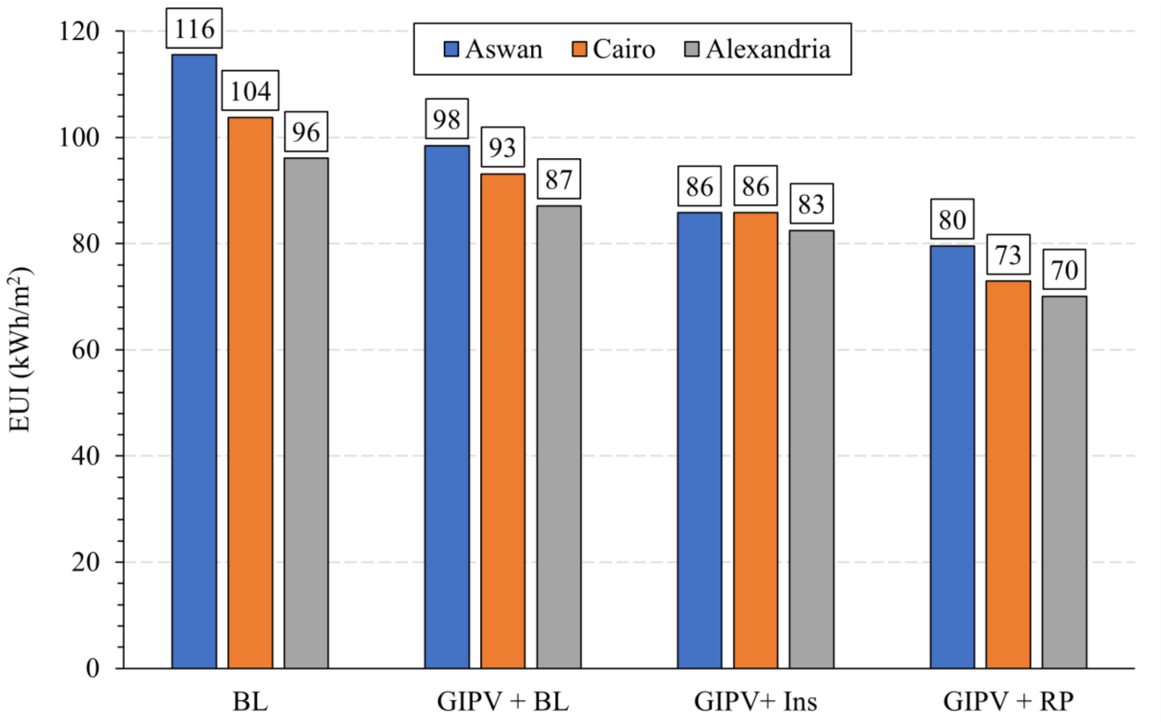

Figure 4-13: EUI response to different implementations

It is noticeable that the modifications tested to improve the energy efficiency and the whole building energy use represented by EUI. The annual GIPV energy generation driven by the decreasing solar intensity from Aswan, Cairo, to Alexandria is 176698 kWh, 152491 kWh, and 141441 kWh. The best solution is the coupling between GIPV with RP, which reduces the EUI in Aswan, Cairo, and Alexandria, by approximately 31 %, 29%, and 27%, respectively. On the contrary, the solution that reduces the EUI values the least is the coupling of GIPV with BL, reaching percentages for Aswan, Cairo, and Alexandria of 16%, 11%, and 9%, respectively.

4.2.2.2 Operational Carbon Emission Assessment

Renewables have boosted economic development and diminished carbon pollution [195]. This subsection summarizes the carbon footprint reductions related to the tested implementations for the three climates under investigation.

In all cases, the highest CO_2 emissions reductions are reached in Aswan, followed by Cairo and Alexandria. The best environmental option is obtained with the integration of GIPV and RP.

Table (4-11) demonstrates the Carbon footprint reductions linked to the implementations.

Table 4-11: Carbon emissions reduction percentage linked to tested models

Model	**Aswan, Egypt**	**Cairo, Egypt**	**Alexandria, Egypt**
	CO_2 Reduction Percentage		
BL	-	-	-
GIPV + BL	15%	10%	9%
GIPV + Ins	26%	17%	14%
GIPV + RP	31%	30%	27%

4.2.2.3 Techno-economic Assessment

An in-depth techno-economic evaluation is being performed using Egypt's present commercial electricity rate. The most recent pricing and costs per meter square of the potential solutions are surveyed and determined to be $110, $3.56, $4 for GIPV, RP, and 25 mm XPS, respectively [22,96]. A techno-economic analysis is conducted, considering both the original and ongoing expenses. The results are compiled in Table (4-12) for Aswan, Table (4-13) for Cairo, and Table (4-14) for Alexandria.

Table 4-12: Techno-economic results for Aswan

Model	**Aswan, Egypt**			
	IRR	**ROI**	**NPV (USD)**	**PBP (Years)**
GIPV + BL	10%	10%	-4,967	6.1
GIPV + Ins	20%	15%	1,169,987	4.1
GIPV + RP	26%	18%	1,959,295	3.3

Table 4-13: Techno-economic results for Cairo

Model	Cairo, Egypt			
	IRR	ROI	NPV (USD)	PBP (Years)
GIPV + BL	0%	6%	-782,695	10
GIPV + Ins	8%	9%	-251,521	6.8
GIPV + RP	22%	16%	1,337,432	3.9

Table 4-14: Techno-economic results for Alexandria

Model	Aswan, Egypt			
	IRR	ROI	NPV (USD)	PBP (Years)
GIPV + BL	-3%	5%	-981,266	11.6
GIPV + Ins	2%	7%	-765,104	8.9
GIPV + RP	17%	13%	760,896	4.6

Tables (4-12), (4-13), and (4-14) show that the R.P merged with the GIPV appears to be the overall highest cost-effective execution for the tested cities with the greatest IRR, ROI, NPV, and the shortest PBP. The effectiveness in Aswan is the most driven by its highest solar intensity, followed by Cairo and Alexandria. A positive NPV occurs when the ROI exceeds the discount rate of 10%, whereas a negative one occurs when the indicator drops below this threshold.

4.2.2.4 Thermal Comfort

In this subsection, the resulting thermal comfort has also been evaluated in Discomfort hours (DCH) and tabulated, as shown in Table (4-15). In all the options evaluated, the greatest reductions in discomfort hours are occurred in Aswan, with Alexandria and Cairo obtaining very similar percentages.

Table 4-15: Resulting DCH reduction percentage for the three locations

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	DCH Reduction Percentage		
BL	-	-	-
GIPV + BL	-	-	-
GIPV + Ins	25%	17%	18%
GIPV + RP	20%	11%	10%

The outcomes highlighted that integrating the GIPV technologies with the insulating materials enhances thermal comfort.

The outcomes of the EUI, CO_2 emissions, as well as the DCHs, are gathered and graphically demonstrated as shown in Figure (4-14) for Aswan, Figure (4-15) for Cairo, and Figure (4-16) for Alexandria. Integrating the reflective paint (RP) solution to reduce the walls' solar radiations absorbance while upgrading conventional glazing to GIPV systems proved its effectiveness in Aswan, followed by Cairo and Alexandria.

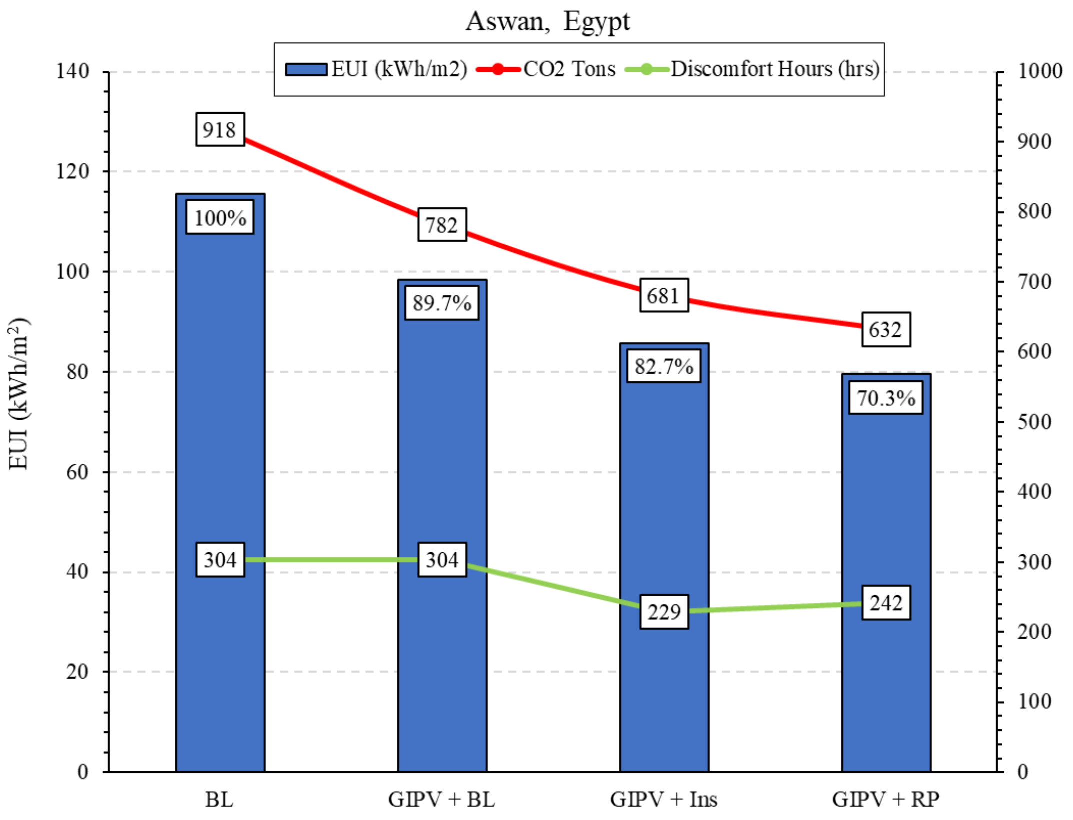

Figure 4-14: Gathered envelope outcomes for Aswan

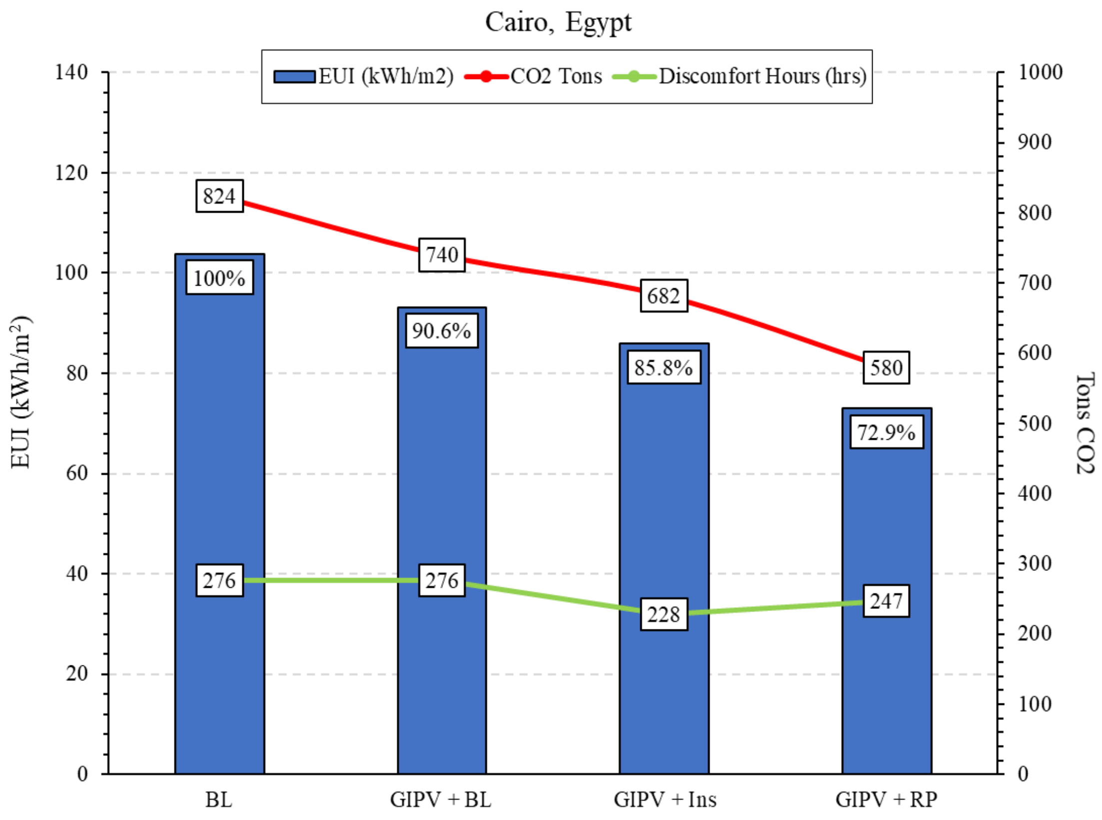

Figure 4-15: Gathered envelope outcomes for Cairo

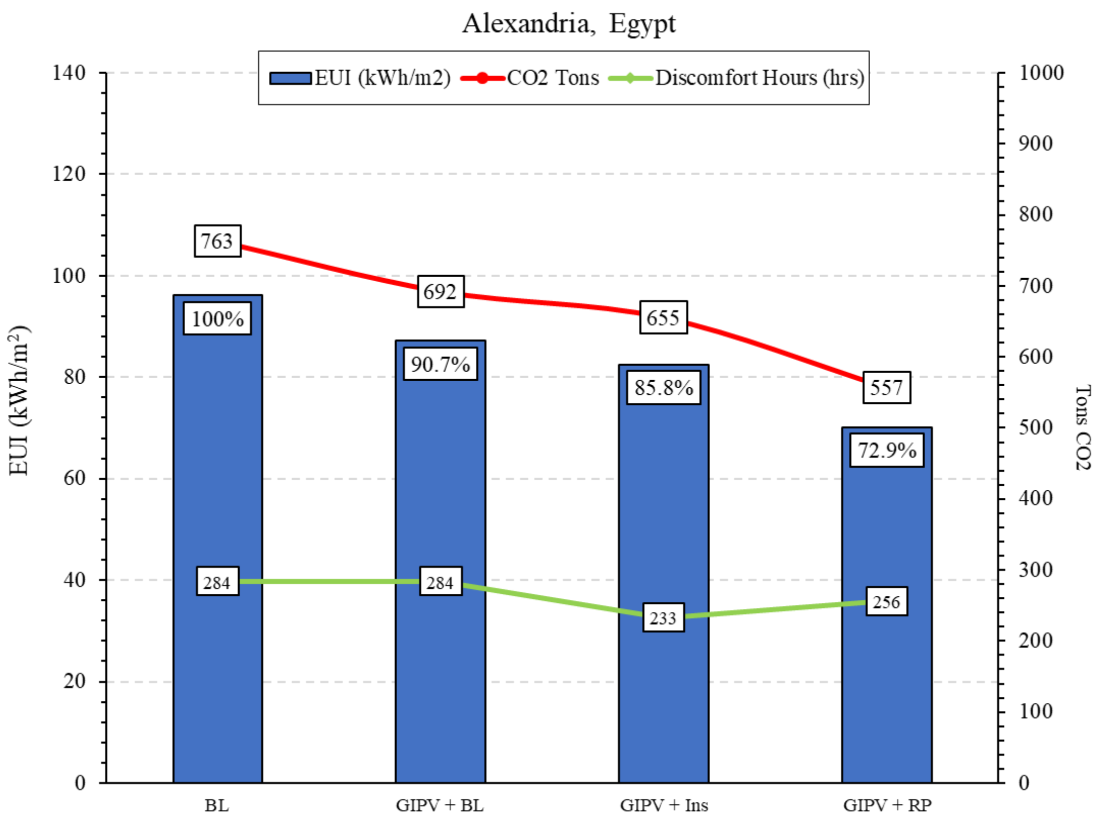

Figure 4-16: Gathered envelope outcomes for Alexandria

4.2.2.5 Proposed Solution and Decision-making

Following the same weighting methodology, the findings highlighted that GIPV integrated with conventional 25 mm XPS thermal insulation material decreases DCHs. However, an overall balanced decision considering the whole system approach recommends the implementation of GIPV along with reflective paints derived by the least EUI, highest CO_2 emission reductions, and a noticeable decrease in DCHs as gathered in Tables (4-16), (4-17), and (4-18) for the three locations. Along with these parameters, the recommended model has proved the highest economic revenue, as shown previously in Tables (4-12), (4-13), and (4-14) for the three locations.

Table 4-16: EUI, CO_2 reduction percentage, and DCHs reductions, Aswan

Model	Aswan, Egypt		
	EUI (kWh/m^2)	**CO_2 Reduction**	**DCH Reduction**
BL	116	-	-
GIPV + BL	98	15%	-
GIPV + Ins	86	26%	25%
GIPV + RP	80	31%	20%

Table 4-17: EUI, CO_2 reduction percentage, and DCHs reductions, Cairo

Model	Cairo, Egypt		
	EUI (kWh/m^2)	**CO_2 Reduction**	**DCH Reduction**
BL	104	-	-
GIPV + BL	93	10%	-
GIPV + Ins	86	17%	17%
GIPV + RP	73	30%	11%

Table 4-18: EUI, CO_2 reduction percentage, and DCHs reductions, Alexandria

Model	Alexandria, Egypt		
	EUI (kWh/m^2)	**CO_2 Reduction**	**DCH Reduction**
BL	96	-	-
GIPV + BL	87	9%	-
GIPV + Ins	83	14%	18%
GIPV + RP	70	27%	10%

Following the weighting methodology, the proposed integration reduces the energy utilization and CO_2 emissions in Aswan followed by Cairo, and Alexandria while enhancing the thermal comfort.

Energy scholars and professionals could exploit these findings to advance analysis on GIPV and on executing practical energy-efficient options, particularly in hot environments, in which it would significantly reduce energy consumption, enhance clean energy generation, achieve better comfort conditions, and provide a viable, sustainable substitute to traditional classic fossil fuel capabilities.

4.3 HVAC Systems

According to numerous assessments, HVAC systems constitute nearly half of a building's overall energy utilization [7,12,13,27,97,98]. Furthermore, the outbreak of the COVID-19 pandemic and Mucormycosis were strongly tied to the dispersion of infectious aerosols in personal interaction in enclosed spaces, highlighting the importance of taking strict and effective measures to restrict infection rates. Indoor dissemination of MERS-CoV, SARS-CoV-1, and respiratory infections are thought to be accelerated through HVAC systems that have not been designed to acclimate infected humans [105]. Thus, the aerosol formation, along with the wide variety of viral loads observed among patients, mandates customizing HVAC systems' safety to the specialized control needs.

Building designers spend extensive efforts and time designing HVAC solutions that incorporate simultaneous ventilation and moisture control functions. In high-use areas, such as with classrooms, the use of a system providing a fixed amount of fresh air mixed with recirculated return air can be a dilemma. This is since sensible and latent cooling loads do not peak simultaneously on the HVAC equipment. Ordinarily, the standard HVAC system is chosen with enough cooling capacity to maintain specified design load mostly at the highest outside dry bulb temperature and is controlled through a thermostat that aligns the sensible cooling capacities of both the coil and the room [196]. As a result, when the room's sensible load decreases, the HVAC equipment's total cooling capacity, including both sensible and latent, reduce. The conjunction of decreased latent cooling capacity and the room’s low sensible heat ratio (SHR) raises indoor moisture levels.

This increased indoor moisture level is no more affecting the indoor thermal comfort alone, but with the growing attention to health concerns, especially airborne dissemination, numerous guidelines and references restricted humidity levels to specific conditions [107–

109,197,198]. Taking all these into consideration, the current situation emphasizes the need for an energy-efficient HVAC system for current and future epidemic preventative measures incorporating multiple simulations.

4.3.1 HVAC and Built Environment

The primary role of HVAC is to maintain the temperature and relative humidity of the conditioned zones within acceptable limits while considering air quality, velocity, and noise levels. Whenever the dehumidification load is higher, either owing to massive indoor moisture production or sometimes significant fresh airflow rates, the cooling-dehumidification systems in several HVAC systems are incapable of appropriately fulfilling the required load demands of the property [196]. As a result, inappropriate design and operation of HVAC systems for moisture control will result in unsatisfactory indoor environmental quality and excessive energy consumption [196].

Depending on how conditioned air is delivered, central HVAC systems can be subdivided into four broad categories, terminal units such as FCU, All-Air systems such as CAV, VAV, and a blended approach, DOAS.

FCU, illustrated in Figure (4-17), is widely used equipment that recirculates the indoor airflow in a zone across a cooling/heating coil. They often necessitate a supplementary ventilation method, and thus, in terms of ventilation, they are inefficient when contrasted to conventional VAV solutions.

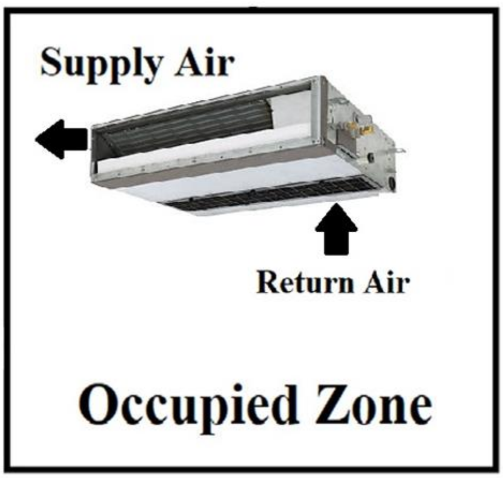

Figure 4-17: FCU system arrangement

In high-inhabitant facilities, the reuse of conditioned air through CAV, illustrated in Figure (4-18), and VAV, Figure (4-19) systems simply supplies conditioned air, a combination of outdoor and return air, to more than one ventilated zone [160]. Such zones may have varying percentages of outdoor air, as stipulated by ASHRAE. Yet, an air handling unit supplies only one percentage, indicating that the fresh air flow rate of the air handling unit is governed by the zone demanding the greatest outside air portion [160]. Hence, over/excessive ventilation occurs in various surrounding zones. Additionally, HVAC systems typically act on regulating the temperature indoors, while it has been well recognized that temperature and humidity, if not adequately maintained, viral dissemination can facilitate [99,106].

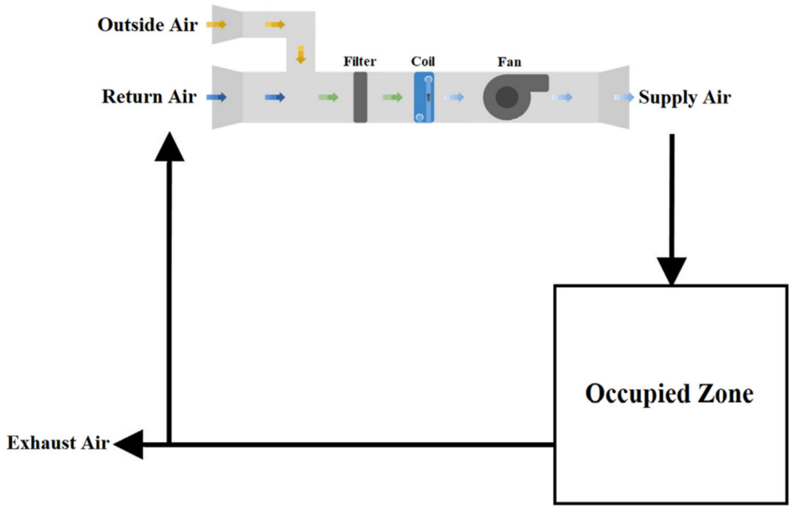

Figure 4-18: CAV system arrangement

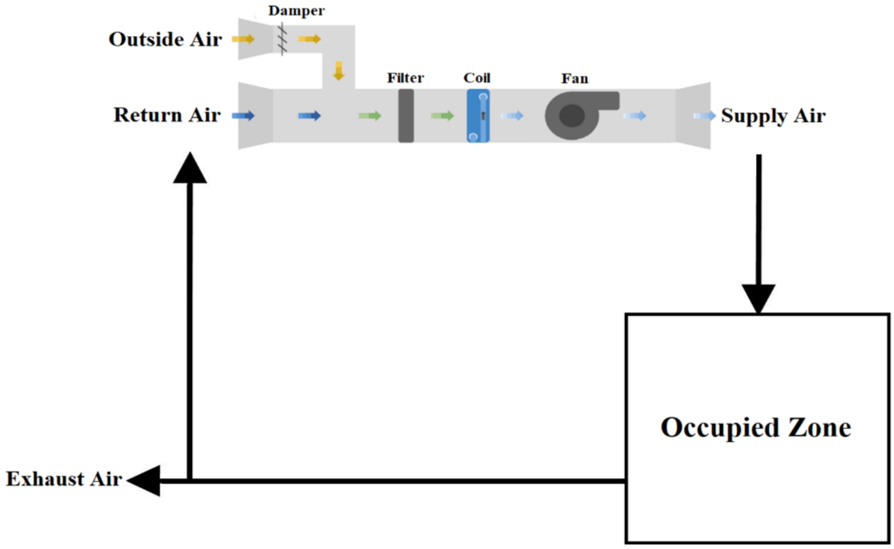

Figure 4-19: VAV system arrangement

The DOAS, demonstrated in Figure (4-20), is a potentially viable HVAC option that provides the exact quantity of required outdoor air desired for ventilation purposes by every zone [7,13,99]. The ventilation air is delivered at low dew-point values, aiding in absorbing both the latent and a portion of the sensible load of the zone, thereby decoupling both loads [7,13,199].

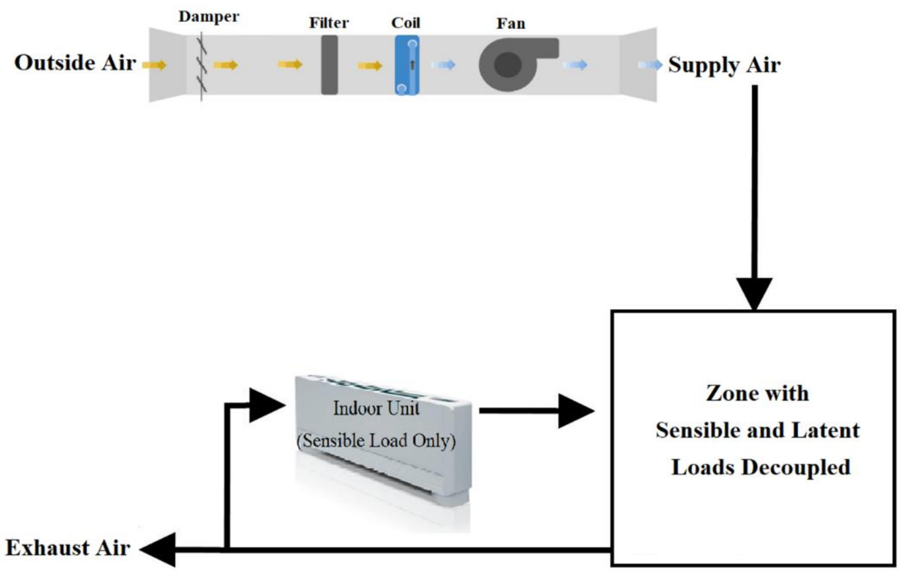

Figure 4-20: DOAS system arrangement

To efficiently introduce an advantageous solution for hot climatic zones, HVAC solutions are evaluated, and the building's overall performance is addressed on a yearly basis, analogous to the approach of Chirico and Rulli [106] in analyzing indoor thermal environments challenges.

4.3.1.1 Temperature and Humidity Control

Regarding thermal comfort, temperature and relative humidity are the two main parameters affecting indoor environmental quality [200–203]. Before executing the systems to the three cities, the simulations have been conducted for the validated building in Cairo in terms of indoor temperature and relative humidity control. Following the simulations, it was observed that various systems almost regulate the interior temperature identically, as represented visually in Figure (4-21). Nevertheless, as per various investigations, moisture content and relative humidity are crucial factors for viral survivability. Accordingly, all models under investigation have been simulated for humidity control evaluation, as illustrated in Figure (4-22).

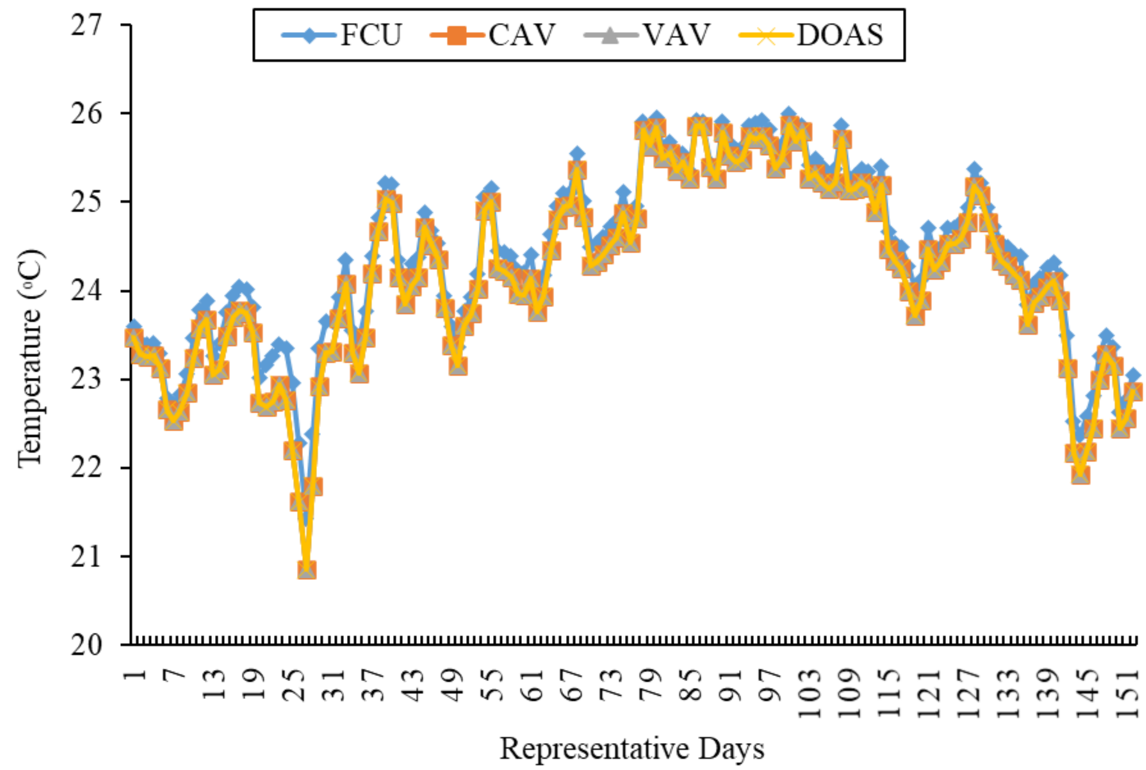

Figure 4-21: Indoor temperature related to tested HVAC systems, Cairo baseline

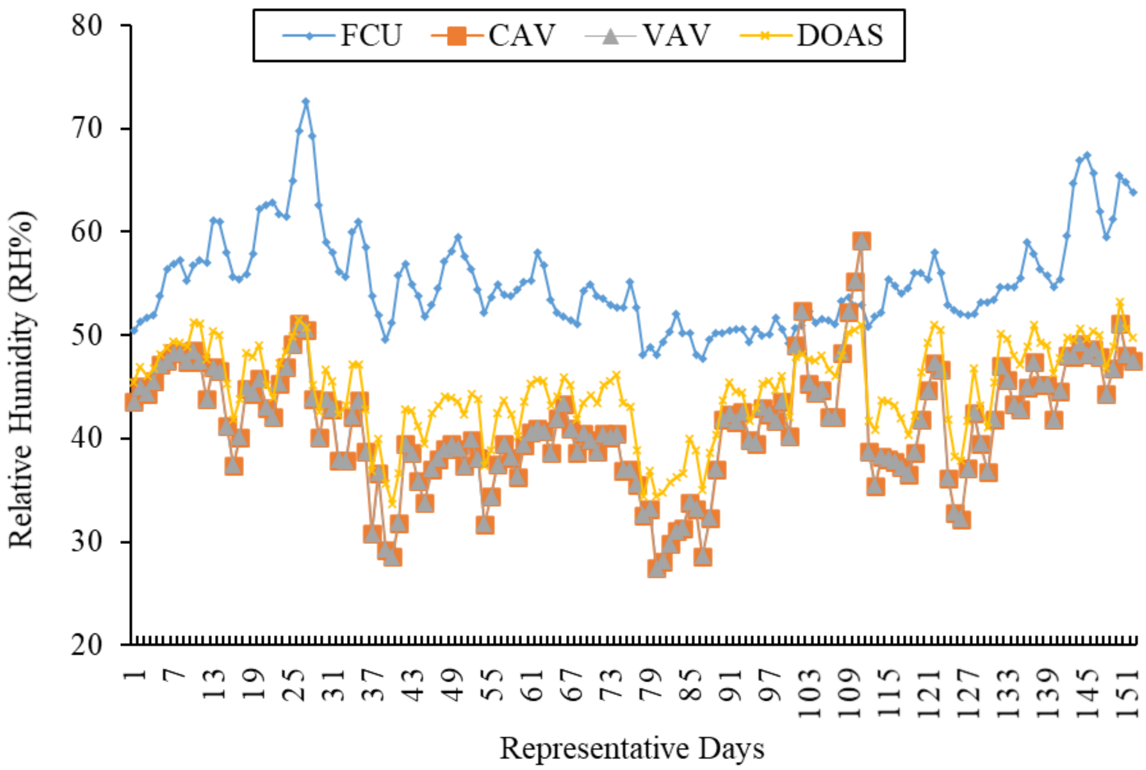

Figure 4-22: Indoor relative humidity related to tested HVAC systems, Cairo baseline

It is clearly identified from the simulation outcomes that the FCUs perform the worst in terms of managing indoor humidity levels. Although their working parameters vary, the indoor air quality delivered by CAV and VAV units is nearly identical. The CAV alters the supply temperature to accommodate internal loads while maintaining a fixed supply airflow rate. In contrast, the VAV maintains a set temperature but varies the supply airflow rate, which indeed has a beneficial impact on energy. The computations demonstrated that the recommended DOAS has viable autonomous temperature and humidity control.

4.3.1.2 Building Energy Performance

Furthermore, the simulations assessed the overall performance of the entire building for the three locations in terms of whole-building energy consumption, HVAC energy use, as well as operational CO_2 emissions.

Figure (4-23) illustrates the energy utilization (left Y-axis) as well as the operational CO_2 emissions (right Y-axis), contrasted to the tested HVAC systems (X-axis) for Aswan, while Figure (4-24) shows Cairo and Figure (4-25) represents Alexandria.

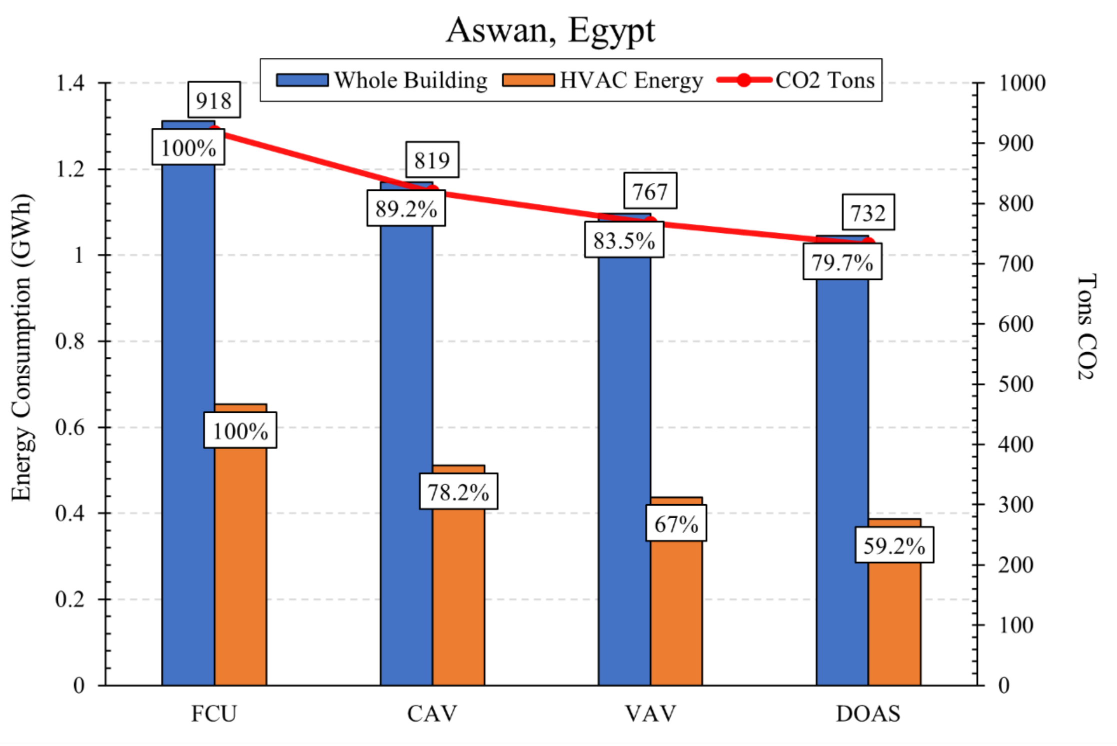

Figure 4-23: Building and HVAC performance related to HVAC systems, Aswan

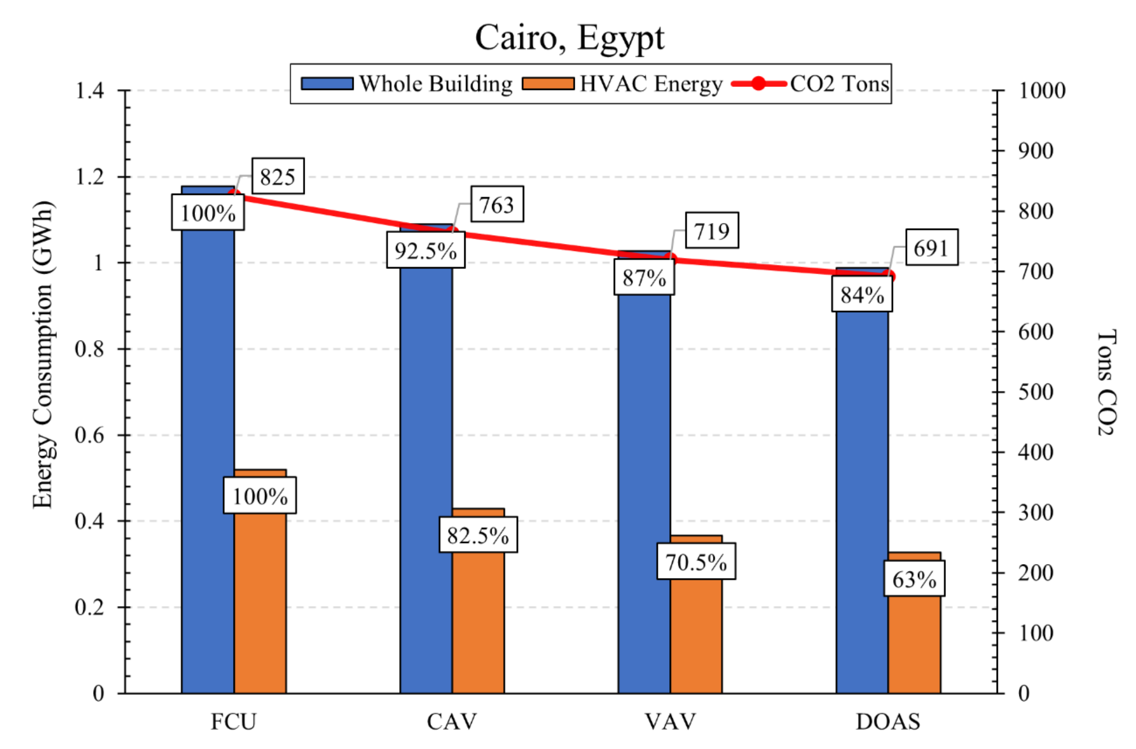

Figure 4-24: Building and HVAC performance related to HVAC systems, Cairo

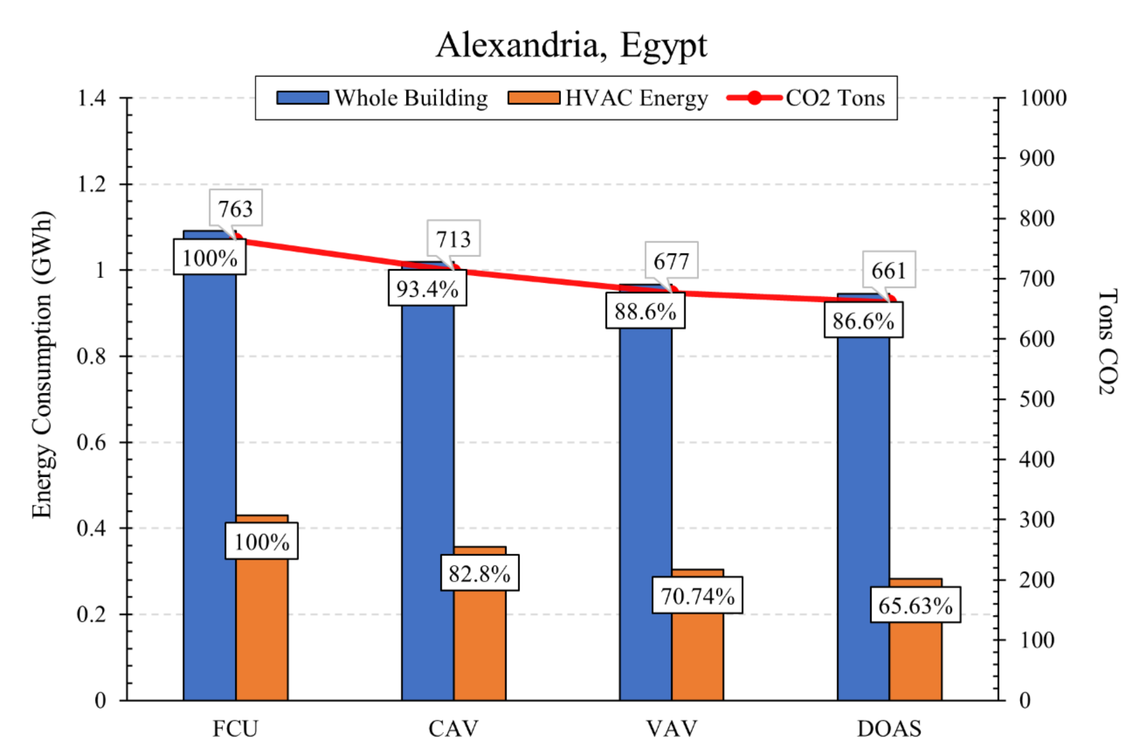

Figure 4-25: Building and HVAC performance related to HVAC systems, Alexandria

The figures represent the whole-building energy consumption and HVAC energy utilization compared to the baseline model. The effectiveness of the DOAS in terms of energy-efficient operation is evident. The achievement in Aswan is the highest derived by its highest outdoor conditions, followed by Cairo and Alexandria. However, the systems have been subjected to a full techno-economic assessment.

4.3.1.3 Techno-economic Assessment

The presented systems will be subject to a cost comparison before implementation. The increased price between the suggested solutions and baseline FCU represents the investment cost. Based on Egypt's observed costs, the economic assessment outcomes per system are shown in Table (4-19) for Aswan, Table (4-20) for Cairo, and Table (4-21) for Alexandria.

Table 4-19: HVAC systems techno-economic assessment, Aswan

Model	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
FCU	1.31	0.65	133,315	-	-	-
CAV	1.17	0.51	118,926	14,388	3.0%	20.4
VAV	1.10	0.44	111,414	21,901	3.0%	20.5
DOAS	1.05	0.39	106,266	27,048	14.9%	4.1

Table 4-20: HVAC systems techno-economic assessment, Cairo

Model	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
FCU	1.17	0.52	119,724	-	-	-
CAV	1.09	0.43	110,823	8,900	1.6%	37.3
VAV	1.03	0.37	104,444	15,279	1.9%	31.7
DOAS	0.99	0.33	100,402	19,321	5.8%	10.4

Table 4-21: HVAC systems techno-economic assessment, Alexandria

Model	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
FCU	1.09	0.43	110,866	-	-	-
CAV	1.02	0.36	103,539	7,327	1.2%	48.8
VAV	0.97	0.30	98,248	12,618	1.5%	40.7
DOAS	0.94	0.28	96,012	14,854	3.2%	18.8

In terms of the energy economy, the DOAS reduced the whole-building energy use for Aswan, Cairo, and Alexandria by about 20.3%, 16%, and 13.4%, and HVAC energy use by 40.8%, 37%, and 34.4%. The techno-economic findings highlighted the viability of DOAS, among other systems in the three hot climatic regions with an ROI of 14.9%, 5.8%, and 3.2%

in Aswan, Cairo, and Alexandria. The findings show a potential investment in Egyptian cities, with the highest results achieved in Aswan, Cairo, and Alexandria.

4.3.1.4 Proposed Solution and Decision-making

Once the energy, economic, environmental, and thermal comfort behavior of all the proposed solutions have been quantified, a building model is selected that integrates different measures. This integrated model seeks to optimize the performance of the building studied under different prisms employing a decision matrix process.

Planning and managing systems that supply greater outdoor ventilation air, notwithstanding the cost-effectiveness of the DOAS, is necessary owing to the ongoing global pandemic and future epidemic prevention. While considering required ventilation fresh air, the projected DOAS has demonstrated the potential to support the recommended rates for buildings in an energy-efficient manner.

4.4 Proposed Integrated Model

The viable building envelope solution is then integrated with the DOAS to assess the effectiveness of integration on the whole building performance. The model is considered utilizing the same methodology regarding energy use, carbon emissions, and thermal comfort. Table (4-22) compares the baseline and proposed model characteristics.

Table 4-22: Baseline and proposed model characteristics

Model	**Measures characteristics**		
	Insulation	**BIPV**	**HVAC system**
Baseline model	-	-	FCU
Proposed model	RP	GIPV	DOAS

4.4.1 Building Energy Response

This subsection assesses the response to the integration of the building envelope solution (GIPV + RP) and DOAS, named the Proposed Model. The influence on the whole building energy use and the HVAC energy consumption is graphically illustrated in Figures (4-26) for Aswan, Figure (4-27) for Cairo, and Figure (4-28) for Alexandria.

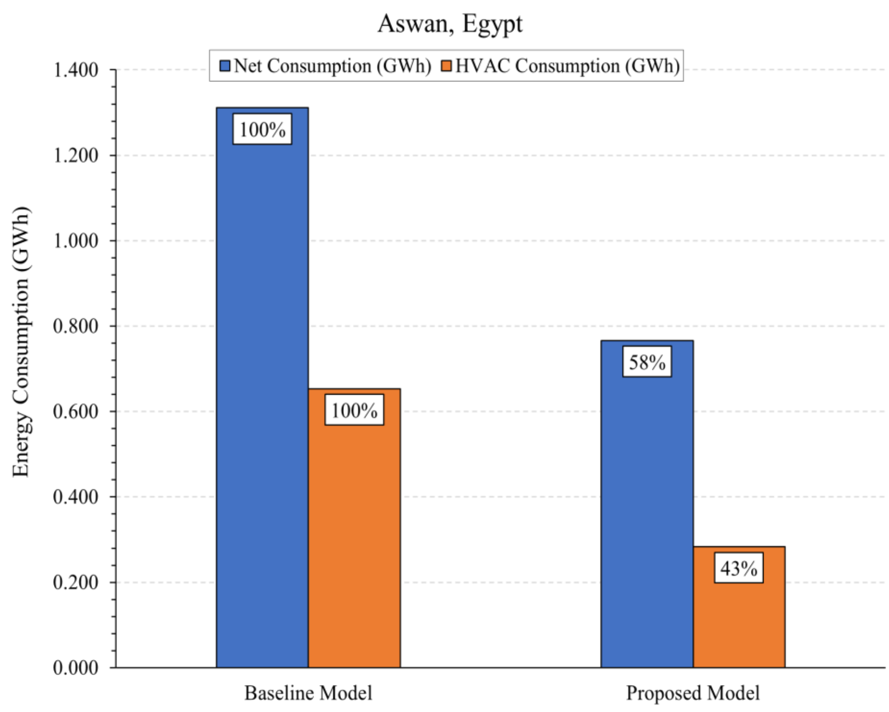

Figure 4-26: Baseline - Proposed model energy use comparison, Aswan

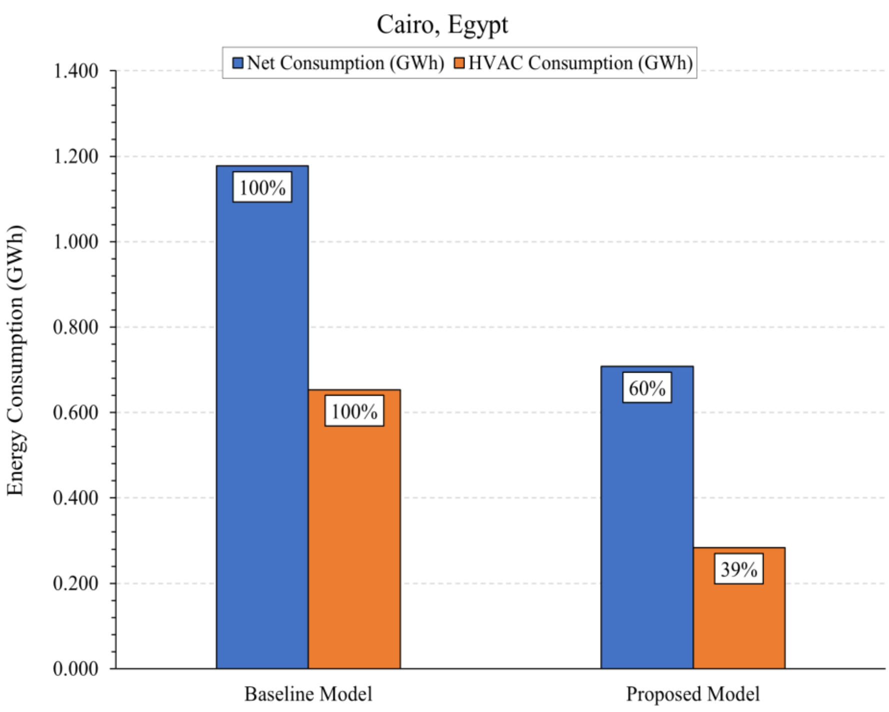

Figure 4-27: Baseline - Proposed model energy use comparison, Cairo

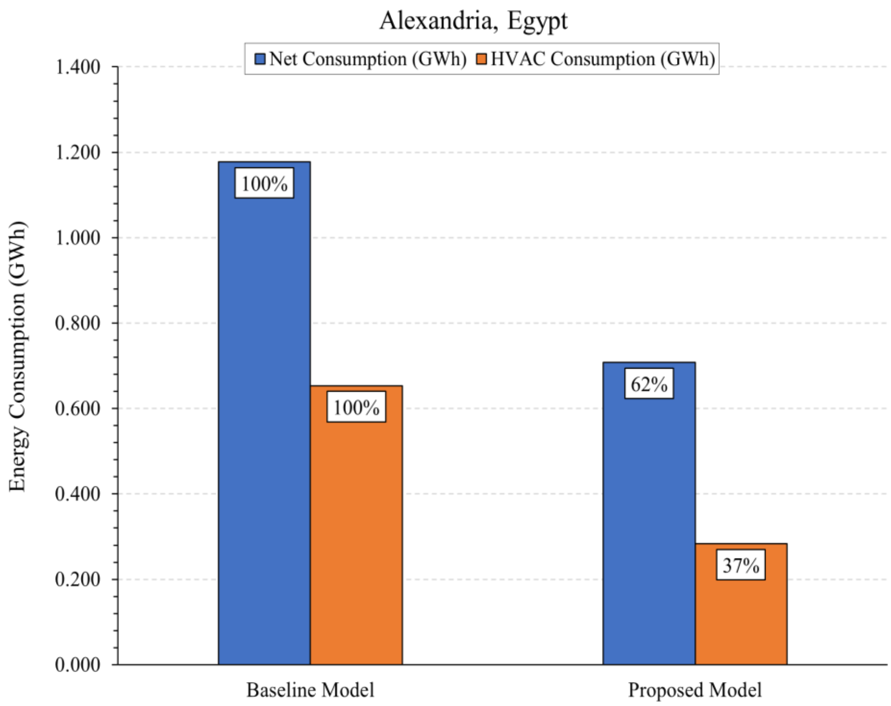

Figure 4-28: Baseline - Proposed model energy use comparison, Alexandria

It is observable from the previous figures that the proposed model reduced the whole building energy utilization, particularly HVAC energy use, for the three cities under investigation. The highest reduction in energy net consumption occurs in Alexandria, followed by Cairo and Aswan. However, the highest energy savings in terms of HVAC consumption occur in Aswan, followed by Cairo and Alexandria.

The EUI of the proposed model is listed in Table (4-23) for the three locations. As it can be seen, the three cities reach fairly similar percentages of EUI savings, ranging between 42%, 40%, and 37% for Aswan, Cairo, and Alexandria, respectively.

Table 4-23: Baseline - Proposed model EUI comparison

Model	**Aswan, Egypt**	**Cairo, Egypt**	**Alexandria, Egypt**
	EUI (kWh/m^2)		
Baseline Model	115.6	103.8	96.1
Proposed Model	67.5	62.4	60.1

4.4.2 Operational Carbon Emission Assessment

This subsection summarizes the Carbon footprint reductions related to the integrated model for the three climates under investigation. The highest environmental reduction has been achieved in Aswan, followed by Cairo ad Alexandria. Table (4-24) demonstrates the Carbon footprint reductions linked to the implementations.

Table 4-24: Proposed model carbon emissions reduction percentage

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	CO_2 Reduction Percentage		
Proposed Model	41.5%	39.8%	37%

4.4.3 Thermal Comfort

In this subsection, the resulting thermal comfort has also been evaluated in DCHs and tabulated, as shown in Table (4-25). As occurs with EUI reductions and CO_2 emissions, the highest savings produced in the hours of discomfort occur in Aswan, followed by Cairo and Alexandria.

Table 4-25: Proposed model resulting DCH reduction for the three locations

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	DCHs Reduction Percentage		
Proposed Model	43.1%	42.4%	37.5%

The outcomes highlighted that the proposed model results in an enhanced thermal condition, emitting less CO_2 emissions and having more efficient EUI values.

4.4.4 Techno-economic Assessment

As with all previous models, the model is subjected to an economic assessment to test its applicability. The outcomes are tabulated in Table (4-26) for Aswan, Table (4-27) for Cairo, and Table (4-28) for Alexandria.

Table 4-26: Economic assessment for the Proposed model, Aswan

Model	Whole Building Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
Proposed Model	0.77	77,814	55,332	14%	4.5

Table 4-27: Economic assessment for the Proposed model, Cairo

Model	Whole Building Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
Proposed Model	0.71	71,895	47,677	9%	7.1

Table 4-28: Economic assessment for the Proposed model, Alexandria

Model	Whole Building Energy Use (GWh)	Building Running Cost (USD)	Total Savings	ROI	PBP (Years)
Proposed Model	0.68	69,241	41,485	6%	10

Based on the economic analysis, the model shows an acceptable ROI rate and a short PBP for the three locations under investigation. Aswan shows the highest savings with the highest ROI and the least PBP, followed by Cairo and Alexandria.

4.4.5 Proposed Solution

Designing and executing energy-efficient and pandemic-proof solutions is a significant concern for most planners. With this purpose, a methodology is defined that allows identifying the most appropriate measures based on the building performance, quantifies the proposed measures energetically, environmentally, economically, and comfortably, weighting them in a decision matrix that results in an integrated model.

The outcomes of the proposed integrated model in terms of EUI, CO_2 emissions, as well as the DCHs, are gathered and graphically demonstrated as shown in Figure (4-29) for Aswan, Figure (4-30) for Cairo, and Figure (4-31) for Alexandria. According to the outcomes, the proposed integrated model shows a substantial potential for energy efficiency in the three climatic regions.

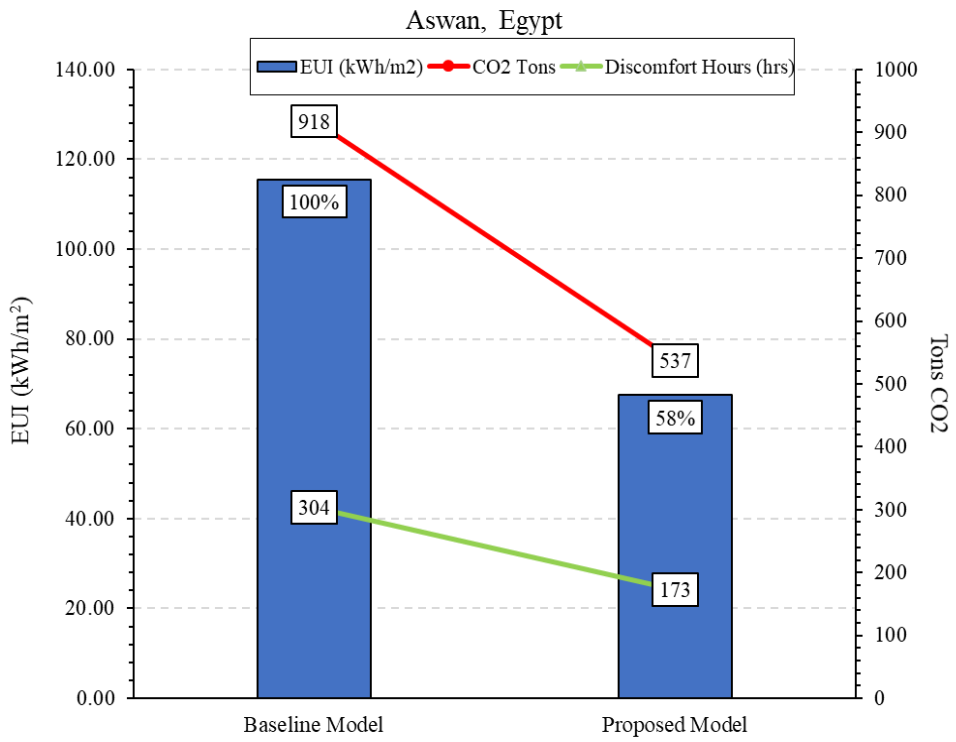

Figure 4-29: Proposed model gathered outcomes, Aswan

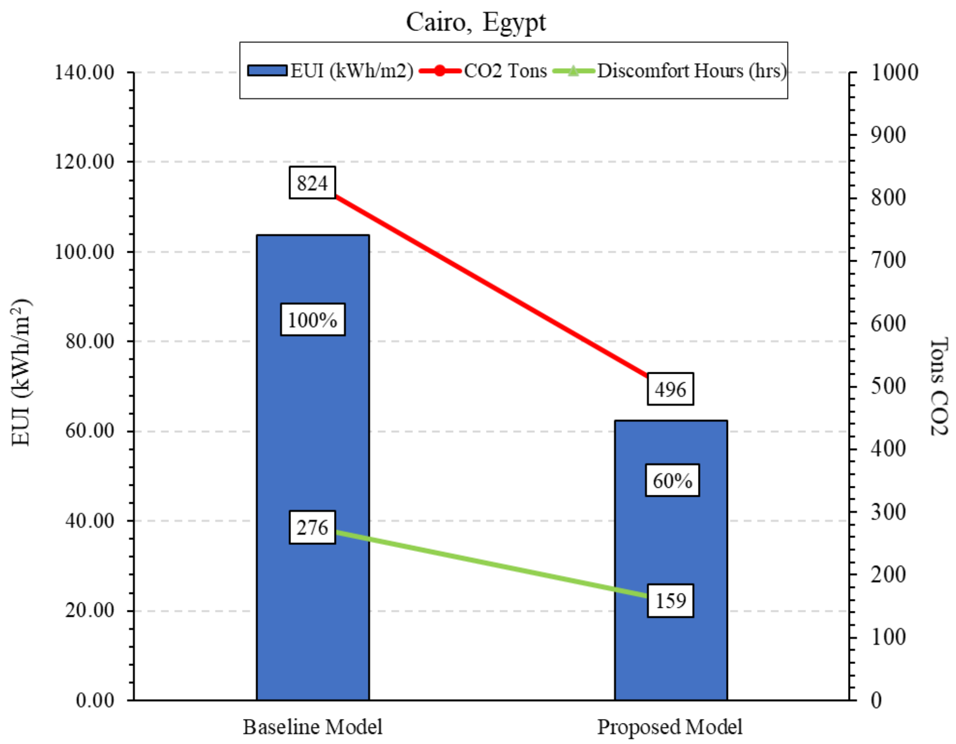

Figure 4-30: Proposed model gathered outcomes, Cairo

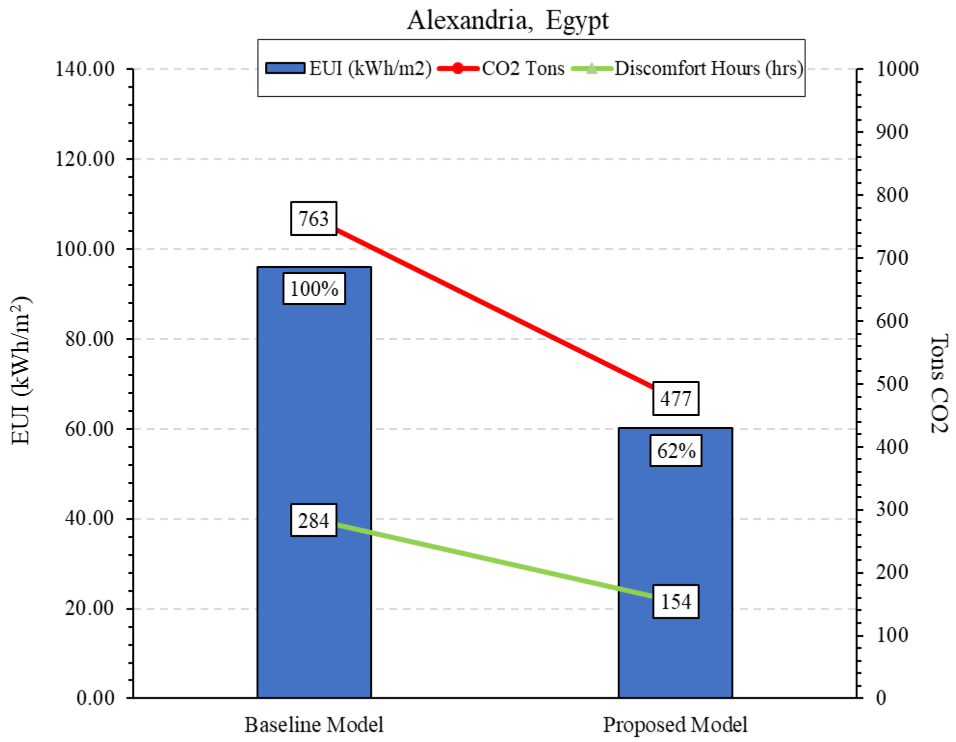

Figure 4-31: Proposed model gathered outcomes, Alexandria

The proposed model demonstrated its applicability through the balanced decision-making methodology, including energy efficiency, eco-friendliness, and thermal comfort enhancement. The whole building energy utilization may be reduced by almost 42%, 40%, and 38% in Aswan, Cairo, and Alexandria. The proposed solution is estimated to pay back its investment in 4.5, 7, and 10 years for Aswan, Cairo, and Alexandria with an ROI of 14%, 9%, and 6%, showing potential for sustainable investment in Egyptian energy sector.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

This dissertation aims to surmount the gap between energy efficiency and inadequate practice in developing nations through emphasizing the value of sustainability and diminishing the carbon emissions of buildings, targeting energy-efficient pandemic-proof buildings. Rather than focusing solely upon one aspect, such as energy use, the study proposes a holistic perspective toward sustainability. Through the design and development of dynamic simulation models, the research investigates the influence of several constructive and operational solutions proposed for an institutional, educational facility on improving energy efficiency, indoor comfort conditions, and environmental consequences. This analysis is carried out in three different locations in Egypt such as Aswan, Cairo, and Alexandria.

The model developed for the current building without any modification, considered as the baseline model, has been validated relying on ASHRAE validation standards, with an NMBE of about 6% and a CVRMSE of nearly 3%, which is acceptable according to this type of validation.

A sensitivity analysis has been carried out, which revealed that the heat gains of the building's thermal envelope account for almost 50% of the total gain, resulting in the HVAC conditioning systems (heating, ventilation, and air-conditioning) consuming nearly half of the entire energy utilization.

Based on the baseline model, constructive solutions have been studied to modernize the thermal envelope of the building, renewable energy installations have been implemented, and low-energy consumption conditioning systems have been investigated in pandemic-proof indoor environments, considering the health crisis situation that currently exists worldwide.

The final proposed model combines a viable building envelope solution with an energy-efficient HVAC condition system to evaluate the improvement produced by this type of integrated solution on the overall building performance.

Finally, a multi-parametric decision-making methodology has been developed, highlighting the following study's conclusions:

1. The external envelope of the building substantially influences the energy use in hot climates, making it essential to increase its energy efficiency.
2. Among the proposed construction solutions, the use of reflective paint is the one that reflects higher increase in energy and environmental performance, followed by the use of extruded polystyrene as insulation.
3. Amongst the traditional insulation materials studied, 25 mm extruded polystyrene is the most cost-effective asset with the greatest IRR, ROI, NPV and the lowest PBP.
4. In the decision-making process, indoor thermal comfort must prevail over other parameters. Based on this, traditional insulations materials can minimize hours of discomfort in hot regions, even though reflective paints are typically the most environmentally friendly option.
5. The results obtained show that reflective paints provide the best solution ~~highest~~ from an environmental and economic point of view, with energy reductions of 21%, 19% and 17%, respectively, as well as drop-in hours of the discomfort of approximately 20%, 7.5% and 3.5% in Aswan, Cairo, and Alexandria respectively (the three climatic zones studied).
6. Relying on balanced decision-making, reflective coatings would be a viable solution for hot climates such as those in Egypt.
7. Photovoltaic solar installations are becoming more and more popular all over the world due to their multipurpose nature since they allow to improve the thermal envelopes of traditional buildings, and at the same time, they produce energy that can be used in the same building.
8. The implementation of photovoltaic solar installations in the three regions studied (Aswan, Cairo, and Alexandria) would allow energy savings of around 15%, 10%, and 9%, respectively.
9. The results obtained show that the implementation of these renewable energy installations, together with the use of reflective paints, would achieve a significant improvement in the sustainability of the building, reducing the energy utilization and operational CO_2 by almost 31%, 29% and 27%, respectively in the three regions studied.

10. The integration of photovoltaic solar installations and reflective coatings insulations could reduce the hours of discomfort in Aswan, Cairo, and Alexandria by about 20%, 11% and 10%, respectively.
11. The integrated models of the building envelope show promising economic outcomes with the highest IRR, ROI and NPV values and ~~a~~ PBP of less than five years for the three climatic regions studied.
12. Among the conditioning systems studied, the DOAS showed an effective indoor environmental quality control in terms of humidity levels regarding HVAC systems, reducing the risk of airborne transmission infections and assuming an important step to achieve future global pandemic-proof HVAC facilities.
13. Compared to several air conditioning systems widely used, DOAS shows excellent potential in reducing HVAC energy utilization and whole-building energy use, with a reasonable economic revenue and payback period.
14. The integrated model finally proposed combines reflective paint as an insulating material for the building envelope, the integration of photovoltaic in glazing and a DOAS conditioning system.
15. The results obtained show that the proposed model manages to reduce energy use and environmental impact by approximately 41.5%, 39.8%, and 37%, while enhancing indoor thermal comfort by 43.1%, 42.4%, and 37.5% in Aswan, Cairo, and Alexandria, respectively, with promising economic measures.

Given the results obtained in this thesis, energy regulations for the construction of new buildings and the rehabilitation of existing ones in developing countries should establish minimum requirements to achieve an improvement in energy efficiency. Globally, policymakers should have among their main objectives the minimization of the greenhouse effect caused by the energy consumption of buildings, the improvement of indoor thermal conditions and the implementation of pandemic-proof solutions.

5.2 Recommendations for Future Work

With this research, together with the efforts of other colleagues, the aim is to improve and provide a solid basis for future policies regarding the construction of new buildings and the rehabilitation of existing ones, taking into account energy efficiency criteria.

Below are some recommendations for future work are presented:

1. Explore the influence of climatic design parameters on the cooling capacity with an in-depth analysis of climatic conditions throughout the summer season for different climates.
2. Analyse the whole-building performance with undersized HVAC equipment.
3. Study the impact of ventilated facades on energy use, CO_2 emissions, and indoor thermal comfort conditions.
4. Extend the investigation to accommodate a wider range of buildings with different activities utilizing the proposed methodology.
5. Evaluate the daylighting influence on the building performance using the proposed methodology.
6. Investigate the influence of occupants' behaviour on the whole-building performance.
7. Perform a detailed analysis of thermal comfort using on-site measurements in the light of the Internet of Things (IoT).

6. CONCLUSIONES Y RECOMENDACIONES PARA FUTUROS TRABAJOS

6.1 Conclusiones

Esta tesis pretende contribuir a vencer la brecha existente entre una adecuada eficiencia energética y las prácticas de construcción utilizadas en los países en vías de desarrollo, enfatizando el valor de la sostenibilidad y disminuyendo las emisiones de gases efecto invernadero producidas por los edificios, para lograr en un futuro cercano edificios eficientes energéticamente a pruebas de pandemias. En lugar de centrarse en un único aspecto, como el uso de la energía, el estudio propone una perspectiva holística hacia la sostenibilidad del entorno construido. Mediante el diseño y el desarrollo de modelos de simulación dinámicos, se investiga la influencia que tienen una serie de soluciones constructivas y operacionales, planteadas para un edificio educativo institucional, en la mejora de la eficiencia energética, en las condiciones de confort interior y en las consecuencias ambientales. Este análisis se lleva a cabo en tres ubicaciones distintas de Egipto, como son Aswan, El Cairo y Alejandría.

El modelo desarrollado para el edificio actual sin ninguna modificación, considerado como caso base, ha sido validado según los estándares de validación de ASHRAE, con un NMBE de alrededor del 6% y un CVRMSE de casi el 3%, valores aceptables para este tipo de validaciones.

Se realizó un análisis de sensibilidad que reveló que las ganancias de calor de la envolvente térmica del edificio suponen casi un 50% de la ganancia total, lo que da lugar a que los sistemas de climatización HVAC (calefacción, ventilación y aire acondicionado) consuma casi la mitad del total de la energía utilizada.

En base al modelo de referencia, se han estudiado soluciones constructivas que modernicen la envolvente térmica del edificio, se han implementado instalaciones de energías renovables y se han investigado sistemas de acondicionamiento de bajo consumo energético para conseguir ambientes interiores a prueba de pandemias, teniendo en cuenta la situación de crisis sanitaria que existe actualmente a nivel mundial.

El modelo final propuesto combina una solución viable para la envolvente del edificio con un sistema de acondicionamiento HVAC energéticamente eficiente para evaluar la mejora producida por este tipo de medidas integradas en el comportamiento general del edificio.

Finalmente, se ha desarrollado una metodología de toma de decisiones multi-paramétrica destacando las siguientes conclusiones del estudio:

1. La envolvente térmica del edificio influye de manera sustancial en el uso de la energía en regiones climáticas cálidas, por lo que es fundamental mejorar la eficiencia energética de la misma.
2. Entre las soluciones constructivas planteadas, el uso de pintura reflectante es la que refleja un mayor incremento en el rendimiento energético y medioambiental, seguida del uso del poliestireno extruido como aislamiento.
3. Entre los materiales de aislamiento tradicionales estudiados, el poliestireno extruido de 25 mm es el que presenta una mejor rentabilidad con los mayores valores de TIR, ROI, NPV y el menos valor de PBP.
4. En el proceso de toma de decisiones, el confort térmico interior debe prevalecer frente a otros parámetros. En base a esto, los materiales de aislamiento tradicionales pueden minimizar las horas de disconfort interiores en las regiones cálidas, aunque se ha observado que el uso de pinturas reflectantes es la opción más respetuosa con el medio ambiente.
5. Los resultados obtenidos reflejan que la pintura reflectante es la mejor solución desde el punto de vista medioambiental y económico, con reducciones en el uso de la energía (tomando como referencia el caso base) del 21%, 19% y 17%, respectivamente, y una caída en las horas de disconformidad de aproximadamente 20%, 7,5% y 3,5% en Aswan, El Cairo y Alejandría, respectivamente (las tres zonas climáticas analizadas).
6. Basándose en una toma de decisiones equilibrada, las pinturas reflectantes serían una solución viable para climas cálidos como los que hay en Egipto.
7. Las instalaciones solares fotovoltaicas son cada vez más populares en todo el mundo debido a su naturaleza polivalente, ya que permiten mejorar las envolventes térmicas de los edificios tradicionales y al mismo tiempo, producen energía que puede ser utilizada en el mismo edificio.
8. La implementación de instalaciones solares fotovoltaicas en las tres regiones estudiadas (Aswan, El Cairo y Alejandría) permitiría alcanzar un ahorro en el

consumo energético de alrededor del 15%, 10% y 9%, respectivamente en cada una de las regiones.

9. Los resultados obtenidos muestran que la implementación de estas instalaciones de energías renovables junto con el uso de pinturas reflectantes, lograrían una mejora significativa en la sostenibilidad del edificio, reduciendo el uso de la energía y las emisiones de CO_2 en casi un 31%, 29% y 27%, respectivamente en las tres regiones estudiadas.
10. La integración de instalaciones solares fotovoltaicas y aislamientos de revestimientos reflectantes lograrían recudir las horas de disconformidad en Aswan, El Cairo y Alejandría en aproximadamente un 20%, 11% y 10%, respectivamente.
11. Los modelos integrados de la envolvente del edificio muestran unos resultados prometedores desde el punto de vista económico, con los valores del TIR, ROI y VAN más altos y un PBP de menos de 5 años para las tres regiones climáticas estudiadas.
12. Entre los sistemas de acondicionamiento estudiados, el DOAS mostró un control de calidad ambiental interior más efectivo en términos de niveles de humedad con respecto a los sistemas HVAC, reduciendo el riesgo de infecciones de transmisión aérea y suponiendo un paso importante para lograr en un futuro instalaciones de climatización a prueba de pandemias globales.
13. En comparación con varios sistemas de climatización (HVAC) ampliamente utilizados, el DOAS muestra un excelente potencial en la reducción del uso de la energía por este tipo de instalaciones y, por tanto, en el uso global de energía en el edificio, con una recuperación de la inversión y período de retorno razonables.
14. El modelo integrado finalmente propuesto combina la pintura reflectante como material aislante para la envolvente del edificio, la integración de fotovoltaica en los acristalamientos y un sistema de acondicionamiento DOAS.
15. Los resultados obtenidos muestran que el modelo propuesto consigue reducir el uso de la energía y el impacto ambiental en aproximadamente un 41,5%, 39,8% y 37%, mientras el confort térmico interior mejora en un 43,1%, 42,4% y 37,5% en Aswan, El Cairoy Alejandría, respectivamente, con unos parámetros económicos también prometedores.

En vista de los resultados obtenidos en esta tesis, las regulaciones energéticas para la construcción de nuevos edificios y la rehabilitación de los ya existentes en los países en vías de desarrollo deberían establecer unos requisitos mínimos para lograr una mejora en la eficiencia energética. A nivel mundial, los responsables políticos deberían de tener entre sus objetivos principales la minimización del efecto invernadero provocado por el consumo de energía de los edificios, la mejora de las condiciones térmicas interiores y la implementación de soluciones a prueba de futuras pandemias.

6.2 Recomendaciones para trabajos futuros

Con esta investigación, junto con el esfuerzo de otros compañeros, se busca mejorar y proporcionar una base sólida para futuras políticas en materia de construcción de nuevos edificios y rehabilitación de los ya existentes, teniendo en cuenta criterios de eficiencia energética.

A continuación, se presentan algunas recomendaciones para trabajos futuros:

1. Explorar la influencia de los parámetros de diseño climático en la capacidad de refrigeración con un análisis en profundidad de las condiciones climáticas a lo largo de la temporada de verano para diferentes climas.
2. Analizar el rendimiento global del edificio con equipos de climatización de tamaño insuficiente.
3. Estudiar el impacto de las fachadas ventiladas en el uso de la energía, las emisiones de CO_2 y las condiciones de confort térmico interior.
4. Ampliar la investigación para dar cabida a una gama más amplia de edificios con diferentes actividades utilizando la metodología propuesta.
5. Evaluar la influencia de la iluminación natural en el desempeño del edificio utilizando la metodología desarrollada.
6. Investigar la influencia del comportamiento de los ocupantes en el rendimiento global del edificio.
7. Realizar un análisis detallado del confort térmico mediante mediciones in situ utilizando el Internet de las Cosas (IoT).

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APPENDIX

This section includes the compendium of manuscripts that have been included in this dissertation in the following order:

1. Techno-economic evaluation of building envelope solutions in hot arid climate: A case study of educational building (https://doi.org/10.1016/j.egyr.2021.07.098)
2. Building envelopes toward energy-efficient buildings: A balanced multi-approach decision making (https://doi.org/10.1002/er.7166)
3. Evaluating heating, ventilation, and air-conditioning systems toward minimizing the airborne transmission risk of Mucormycosis and COVID-19 infections in built environment (https://doi.org/10.1016/j.csite.2021.101567)

A fourth manuscript entitled "Enviro-economic assessment of buildings decarbonization scenarios in hot climates: Mindset toward energy-efficiency" has been *Presented in CEES 2022 and Accepted for Publications in Special Issue in Energy Reports - Elsevier* but is not included as per the publisher's regulations for publication purposes.

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Techno-economic evaluation of building envelope solutions in hot arid climate: A case study of educational building

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Abstract

Building energy use is becoming increasingly important worldwide, with the increasing necessity to attain indoor thermal conditions. The high temperatures in hot climates cause human dissatisfaction resulting in higher use of air conditioning systems. As a result, energy in those buildings rises regularly driven by the increase in the air conditioning systems operation. In the non-residential building sector, the air conditioning system consumes the majority of the building's energy to satisfy the thermal comfort requirements. With this aim, simulations have nowadays become an important tool to fulfill various high-performance buildings. Dynamic simulations have often been used by designers to evaluate buildings' energy performance to accomplish specific goals, as minimizing energy usage and environmental impacts. This study analyzes the energy savings obtained by the execution of retrofitting measures in an educational building located in Egypt through dynamic simulations of the building performance. The main objective is the creation of a decision matrix to select an optimal solution for the building envelope based on the effectiveness of thermal insulation, cost, and environmental factors. Based on the precise physical characteristics of the building's vacancy schedule, geographical location, weather conditions, and the nature of construction, overall energy consumption would be determined. A sensitivity analysis is undertaken to assess the key factors that influence building energy consumption through the validated baseline model. The envelope is chosen as it is vital for the building's energy efficiency and could account for up to 50% of the total heat gain in a building. Thermal insulation is one of the most effective implementations to provide desirable thermal comfort and minimize heat transfer into buildings, resulting in an energy consumption reduction. Two insulation materials are assessed through the building simulation model, the cost of each measure is estimated, and the emissions mitigation produced is obtained. With this information, a decision matrix is created that allows highlighting the best option based on the effectiveness of the measure in Egyptian hot arid climates. Among different insulations surveyed in Egypt, the study highlighted the effectiveness of using Extruded polystyrene insulation (XPS) with a thickness of 25 mm, resulting in reductions of about 16% in Heating, Ventilation, and Air-Conditioning (HVAC) energy consumption and 8% of the overall energy consumption with a payback period of about 25 months and a 29% Return on investment (ROI).

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Nomenclature and Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTO	Building Technologies Office
CO_2	Carbon Dioxide
DBT	Dry Bulb Temperature
DOE	US Department of Energy
EPS	Expanded Polystyrene
GW	Gigawatts
HVAC	Heating, Ventilation and Air Conditioning
kWh	Kilowatt-hours
LPD	Lighting Power Density
PU	Polyurethane
RMSE	Root Mean Square Error
SHGC	Solar Heat Gain Coefficient
U	Overall Heat Transfer Coefficient
WBT	Wet Bulb Temperature
WWR	Window-Wall Ratio
XPS	Extruded Polystyrene

1. Introduction

The electrical installed capacity in Egypt, as of 2018/2019, was 58.353 GW, higher than the expected installed capacity in 2017/2018 of 55.213 GW with an increase of about 6%, according to the latest Egyptian official report [1]. The building sector is typically identified as one of the world's largest energy consumers and accounts for almost two-thirds of world energy demand [2]. In Egypt, the built environment utilizes around 70% of the total energy sold [3]. As buildings massively increase, more energy supply to satisfy new demand would need to increase too. Considering that, a significant proportion of a nation's energy demand is related to the built environment, sustainability action should be taken to minimize energy usage whilst ensuring that human comfort, environmental standards are fulfilled. Global climate change has also had measurable environmental consequences. Scientists have strong expectations that global temperatures will continue to rise over the coming decades, primarily due to greenhouse gasses based on human activities. Scientist claims that by 2050, about 80% of global greenhouse gas emissions are expected to be produced by urban areas [2]. Taking into account the trends produced by climate change, buildings built under outdated designs may not function efficiently. Designers will have to adapt to these changes and propose redesigning spaces, construction techniques, materials used, and efficient retrofit measures in existing buildings. Energy efficiency achievement is one of the most significant aspects, concerning this expectation, several international organizations have stepped up their efforts to promote the implementation of energy-efficient initiatives for building. Green buildings are one of the most common strategies in the last few years around the world. This approach is meant to design highly sustainable buildings, with energy conservation as a high priority. As a consequence, the shift of the built environment towards decarbonization has reached a new era with the extension of the focus on building science and simulations. Due to numerous factors influencing a building's energy usage, such as building envelope, physical characteristics, installed heating–cooling equipment, meteorological conditions, and the behavior of building occupants, estimating building energy performance remains a tough challenge. Large-sized air conditioning systems are required in hot zones however with climate and temperature changes. In developing countries located in hot climatic zones, about 50% of the entire building energy is used for space air conditioning [4–7]. The retrofitting of existing buildings or the introduction of energy-efficient techniques in new designs provides major opportunities to mitigate global energy-related greenhouse emissions. For the large-scale implementation of retrofit strategies, prior knowledge of existing buildings' energy performance is often necessary. A major technical concern, nevertheless, is the strategies for determining the most cost-effective energy reductions for individuals or combinations of retrofit measures for a particular building. Numerous studies have dealt with the application of passive design variables in order to reduce building energy costs under various climatic conditions. In their work, Pargana et al. [8] concentrated on the most popular thermal insulation materials available on the Portuguese market, including XPS, EPS, PU. They concluded that in Portuguese climates, insulation materials have proven to be a successful technique to minimize energy usage and therefore help to achieve sustainable buildings. Ozel [9] in this article examined the efficacy of thermal insulation, with a lifespan of 20 years, used to limit buildings' heat losses and gains under dynamic thermal conditions, using the Turkish climatological data. In steady periodic conditions, the dynamic thermal properties of the building's insulated walls were analyzed using Riyadh climate data with optimized insulation thickness by Al-Sanea and Zedan [10]. Thermal insulation was tested in Greece by Anastaselos et al. [11]. Their research concluded that there was a total energy reduction of around 17%. Finally, they proposed that the implementation of composite systems of external thermal insulation be favored in terms of energy, environmental and economic parameters. Al-Homoud [12] argues in his article that properly treated building envelopes, especially for envelope-load driven residences, can significantly improve thermal performance. Besides, he advocated the use of wall and roof insulation to reduce energy requirements for buildings in all climates. Saleh [13] measured the thermal performance of buildings, in hot-dry climates, with varying configurations, types, and thicknesses of thermal insulation. The improved performance was found when insulation was installed on the exterior surface of the building envelope. The effect of insulation/masonry layer distribution was studied by Bojic and Loveday [14]. It was concluded that: for intermittent heating, insulation/masonry/insulation structure is better, whereas, for intermittent cooling, masonry/insulation/masonry structure is better.

To the best of researchers' knowledge, energy-saving initiatives in hot-arid climatological areas are worthwhile, concurrently, there is a benchmarking gap for thermal insulation importance and selection in Egyptian markets. In this paper, the researchers aim, with the aid of a techno-economic assessment considering the latest available prices on the market, to investigate the effectiveness and the revenue of different building envelope solutions for buildings' owners through a case study of an educational facility accessible to the researchers at Cairo, Egypt.

2. Methodology

An institutional building in Cairo, Egypt, is selected for the examination based on the accessibility of data. The approach used in this study uses DesignBuilder as a building performance simulator to forecast building energy performance. DesignBuilder is considered as it offers a user-friendly interface for the EnergyPlus developed by the DOE's BTO. The methodology, illustrated in Fig. 1, starts with the baseline architectural modeling followed by the implementation of the latest recommended ASHRAE outdoor design conditions [15], the ventilation and internal gains recommended by both ASHRAE 2016 Standards 62.1 and 90.1. The baseline model is validated compared to the building's actual energy consumption measured on-site. The study follows a techno-economic assessment with an environmental impact (CO_2) assessment for a reliable decision.

3. Building description

An educational building located in Cairo; Egypt, hot arid climate [16], has been selected as a case study during this investigation. According to ASHRAE [15], Cairo, Egypt is classified as a Hot-Arid climate (Zone 2B) with a DBT and WBT of 38.2 °C and 21.2 °C. As shown in Fig. 2, the facility comprises six stories representing approximately 11,350 m^2 and usually operates from 08:00 to 16:00 5 days a week. As most institutional buildings worldwide, the building operates with approximately half capacity in August due to annual leaves.

3.1. Building envelope

The baseline model of the building was developed according to Egyptian development and construction industry records. The U-values (W/m^2 K) of the baseline model walls and roof are 1.924 and 2.27 respectively [7]. The on-site, 6 mm Double Blue Glass/6 mm air gap, glazing U-value and SHGC specifications are 3.094 and 0.503 respectively with a WWR of about 30%.

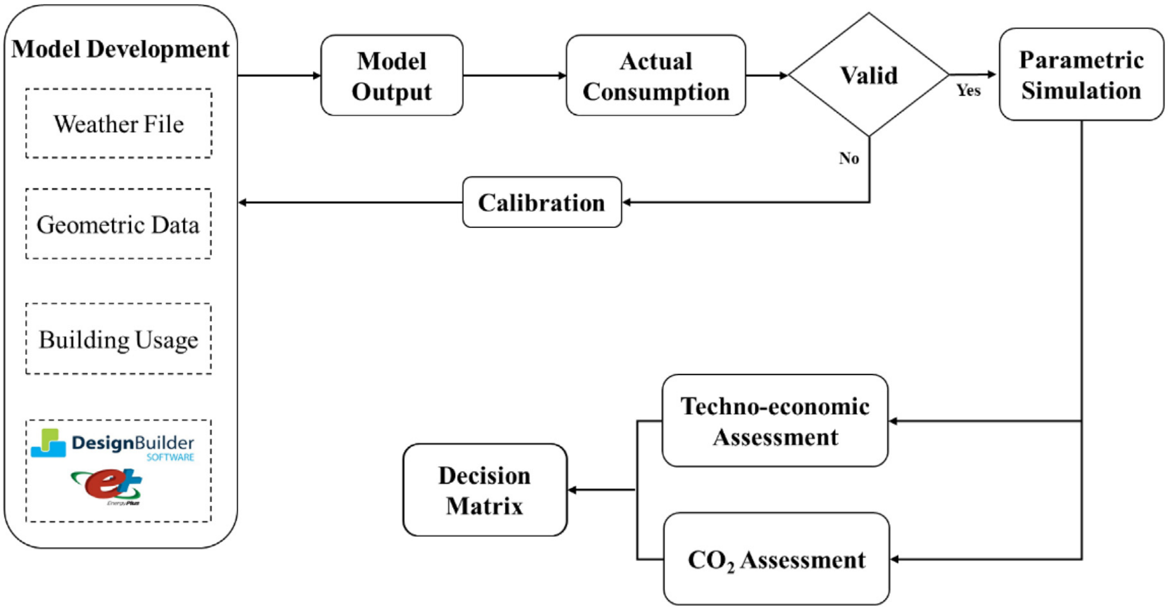

Fig. 1. Modeling flowchart.

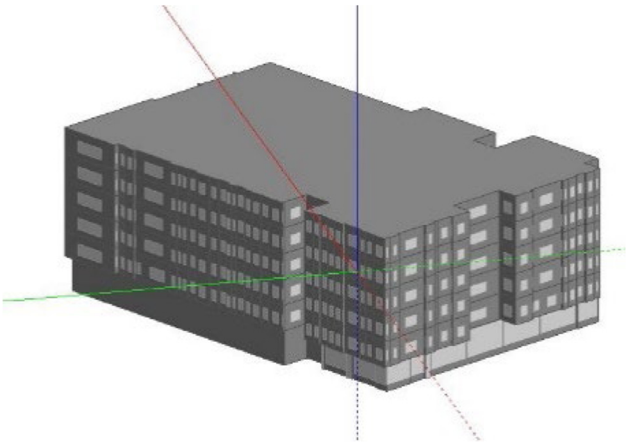

Fig. 2. Baseline model axonometric.

3.2. Internal gains

Internal gains are essentially the inner loads produced indoors, including the occupancy, ventilation rates, lighting, and appliances. Table 1 summarizes ventilation rates, occupant densities [17] along with the recommended LPD using the space-by-space method [18].

3.3. Model validation

There are numerous strategies for validating building energy simulations. These strategies are broadly classified into three categories: analytical, laboratory, and actual techniques, with the third being the highly precise (comparing simulation results to actual data) [19]. The actual validation entails linking data from building measurements with simulation data. In this study, the baseline model is validated compared to the building's actual energy consumption as shown in Figs. 3a and 3b. Error analysis is a vital part of any scientific experiment; therefore, it is crucial to

Table 1. Recommended ventilation rates, occupant densities, and LPD of Institutional buildings.

Zone	Ventilation rate (L/s-person)	Ventilation rate (L/s-m^2)	Occupant density (#/100 m^2)	LPD (W/m^2)
Classroom	3.8	0.3	65	13.4
Coffee Stations	2.5	0.3	20	7
Computer lab	5	0.6	25	18.4
Conference/Meeting	2.5	0.3	50	13.3
Corridors	–	0.3	–	9.9
Laboratories	5	0.9	25	15.5
Lecture hall	3.8	0.3	150	13.4
Libraries	2.5	0.6	10	11.5
Lounge	2.5	0.6	50	7.9
Main entry lobbies	2.5	0.3	10	9.7
Office Spaces	2.5	0.3	5	12
Reception Areas	2.5	0.3	30	5.9
Restaurants	3.8	0.9	70	11.6

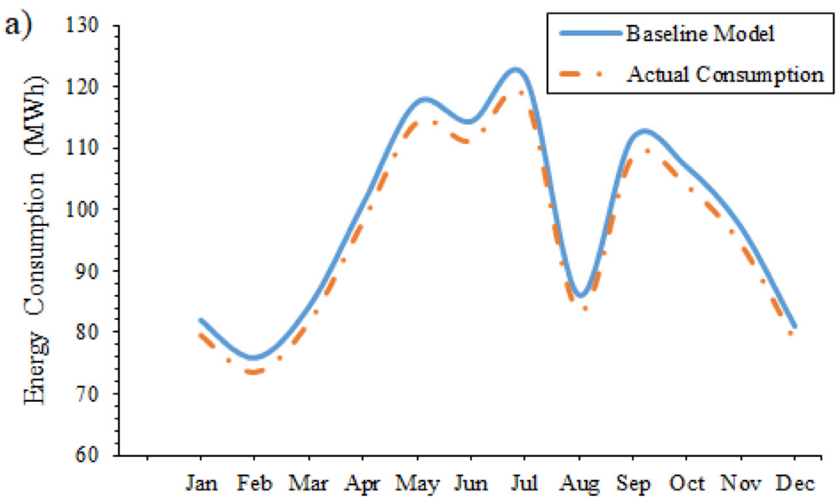

Fig. 3a. Model monthly validation.

estimate the error for any measures. The RMSE for the model is estimated resulting in an acceptable value of 0.2448.

The energy use assessment of the baseline model is carried out by measuring each component's contribution to overall energy usage. Fig. 4 illustrates the monthly energy consumption of each component.

Following the baseline model validation, a sensitivity analysis was carried out showing about 50% of building heat gain is related to the building envelope. About 40% of this heat gain is related to walls and roof. The building's energy breakdown revealed the HVAC contribution to the whole building energy consumption of about 45% which aligns with the HVAC energy consumption in similar climates of [5–7,20,21]

3.4. Thermal insulation

A building's HVAC system aims to maintain a comfortable indoor environment for its occupants. Reducing thermal losses allows for the use of a smaller, more efficient, and less expensive HVAC system significantly reducing HVAC energy consumption. As a result, the energy demand for cooling and heating buildings is reduced, and GHG emissions are reduced. As a consequence, building insulation is a simple but energy-efficient procedure that could be used in the residential and commercial buildings sectors. Thermal insulators consist of materials that have the ability to minimize the heat flow rate due to their high thermal resistance characteristic. The use of thermal insulation

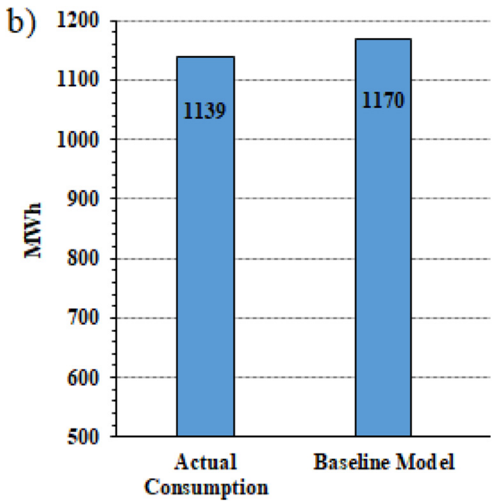

Fig. 3b. Model annual validation.

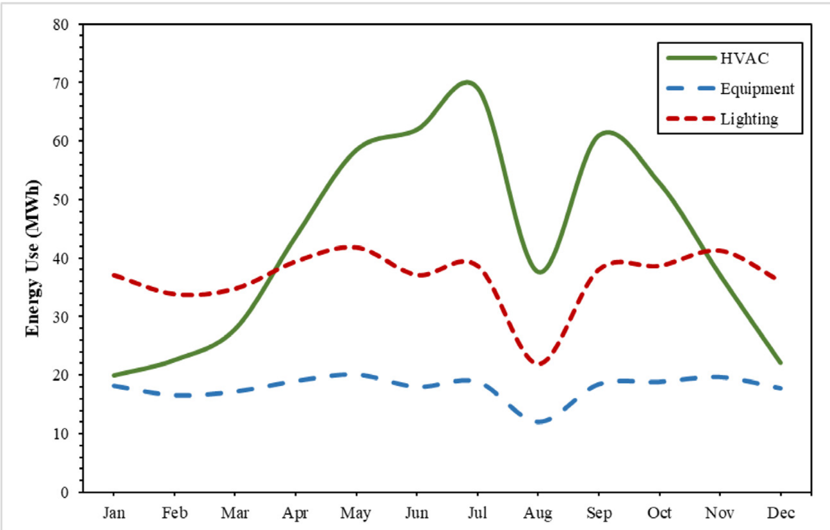

Fig. 4. Monthly baseline model energy analysis (MWh).

on a building results in significant reductions in energy consumption and, as a result, power generation. According to ASHRAE [22], it takes approximately 3 kWh of total energy to generate and deliver 1 kWh to the consumer because electrical energy production and delivery are only around 33% efficient.

Except for the insulation material and thickness, the building characteristics in this analysis remain similar. Two different thermal insulation materials with their thicknesses, available on Egyptian markets 2021, have been evaluated in this study. The two insulations are XPS and PU with thicknesses of 25, 50, 75, and 100 mm, respectively.

4. Results and findings

The outcomes of various thermal insulation variables will be presented in order to assess the impact of each type on energy efficiency. Each parameter was examined independently to determine its effect on the amount of energy consumed.

Table 2. Models Consumption and CO_2 reduction.

Model	Total consumption (GWh)	HVAC consumption (GWh)	CO_2 reduction %
Baseline	1.17	0.52	–
25 mm XPS	1.083	0.429	8.06
50 mm XPS	1.069	0.416	9.19
75 mm XPS	1.063	0.409	9.74
100 mm XPS	1.059	0.405	10.1
25 mm PU	1.093	0.439	7.17
50 mm PU	1.077	0.423	8.52
75 mm PU	1.069	0.416	9.22
100 mm PU	1.068	0.415	9.31

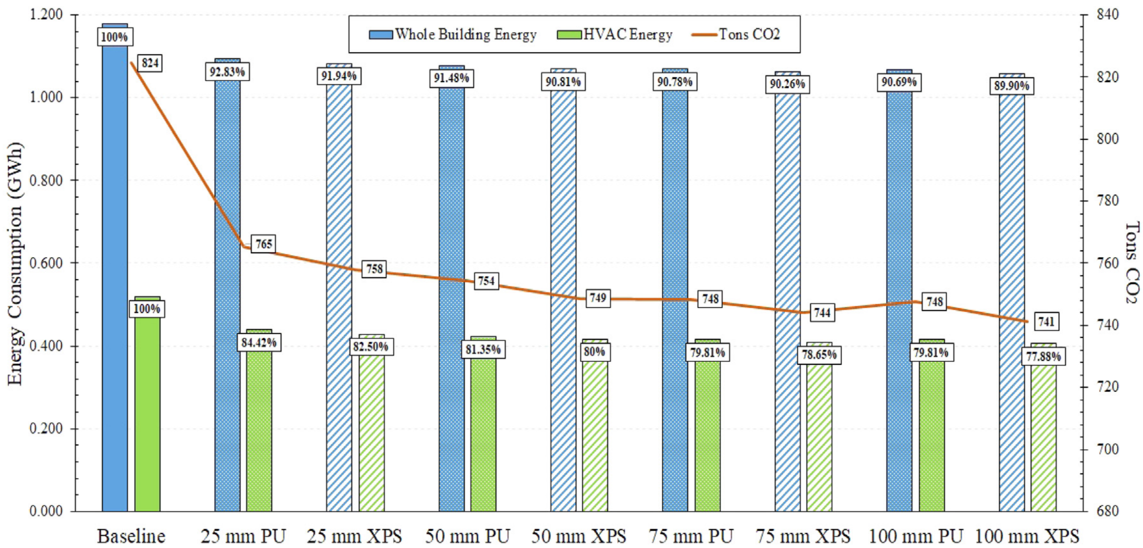

Fig. 5. Energy consumption and CO_2 emissions are related to various models.

The simulation reveals the effectiveness of implementing thermal insulation in Egyptian hot arid climates. Table 2 summarizes the various model response to the entire building energy use, HVAC energy consumption, and resulting CO_2 emission reductions related to the implementation of thermal insulations. Fig. 5 graphically illustrates the thermal insulation materials with different thicknesses related to the building's energy consumption, HVAC energy utilization, and CO_2 emissions.

Table 2 reveals the competitiveness of the building response to different insulations. In such a case, all proposed models should be subjected to a techno-economic analysis for an optimum decision.

As Fig. 5 shows, a minimum of about 7% reduction in energy costs could be accomplished thru the implementation of the minimum thermal insulation thickness of PU. About 60 tons of CO_2 reductions could be achieved through this minimum implementation [23]. The figure also shows the effect of thermal insulations on the HVAC energy consumption for various models. On the other hand, considering the latest Egyptian electricity tariff, in Egyptian pounds (EGP), of 1.6 EGP/kWh for commercial applications [24], the proper selection of thermal insulation based on techno-economic analysis is much preferred. The techno-economic technique represents the optimal implementation through both technical and economic outcomes. Table 3 summarizes the latest insulation cost in EGP. The cost includes the material cost, transportation cost, and fixture cost. The walls and roof areas are 3473 m^2 and 1913 m^2 approximately. Considering both the initial and running costs of the building, a techno-economic analysis [25] is adopted and the outcomes are simply represented in Table 3 along with the increased cost percentage compared to the initial cost.

Table 3. Techno-economic assessment of proposed insulations.

Insulation type	EGP/m^2	Initial cost increase	ROI	Payback period (Years)
25 mm XPS	63	3%	29%	2.1
50 mm XPS	103	5%	21%	2.9
75 mm XPS	140	7%	16%	3.8
100 mm XPS	165	8%	14%	4.3
25 mm PU	115	6%	14%	4.2
50 mm PU	200	10%	10%	6.1
75 mm PU	283	14%	8%	8
100 mm PU	358	18%	6%	10.1

5. Conclusion

The building envelope is a valuable factor for improving energy performance since it has a significant impact on the energy utilization of buildings in hot countries. This study aimed to determine the impact of the insulation materials on the energy efficiency of an institutional building. A valid model was generated using actual building energy data obtained in Cairo, Egypt. Following the model validation, a sensitivity analysis is conducted to quantify the influential factors affecting building energy use. The entire building energy efficiency is assessed depending on the insulation materials to successfully achieve a low energy building in hot environments. The tests reveal the competitiveness of the building response to different insulations. In such cases, it is recommended to undergo a full economic analysis to investigate the cost-effectiveness of the implementation.

The economic analysis showed a wide range of outcomes in terms of ROI and payback periods. To summarize, the economic analysis reveals that 25 mm XPS tends to be the most proper implementation, among the list tabulated in Table 3, with an initial cost increase of 3% and an ROI of 29% and a payback period of about 25 months. Therefore, policymakers in developing countries should legislate the implementation of energy-efficient insulations reducing both energy consumption and carbon footprint.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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RESEARCH ARTICLE

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Building envelopes toward energy-efficient buildings: A balanced multi-approach decision making

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Summary

The worldwide environmentally friendly trend has focused the last decade on emphasizing the value of energy conservation and reducing the carbon footprint in buildings, achieving zero energy buildings. Presently, viable building techniques, in developing countries, are insufficient to achieve zero energy buildings. Thus, authorities should implement policies mandating new developments and renovations to establish "energy-efficient buildings"; nevertheless, design solutions should be properly evaluated and assessed preceding execution. The conservation of energy without jeopardizing human comfortability is a huge challenge for any designer. Occupants are less interested in making a major investment to save some expenses over the next two decades, especially nowadays that energy is still affordable. Therefore, improved indoor environmental conditions are perhaps another important parameter toward energy-efficient buildings. Through dynamic simulations, this study examines the energy efficiency and thermal comfort achieved by integrating retrofitting strategies in an institutional building in three different American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) hot climate zones represented by three cities of Egypt (Aswan, Cairo, and Alexandria). The built-up baseline model is validated using actual energy usage data. The validated baseline model is then subjected to local sensitivity analysis to determine the driving parameters influencing the building's energy demand. The study at hand focuses on a broader perspective on sustainability. With a multiapproach decision-making methodology based on the most recent measures, the study highlights the outcomes through an environmental–economic assessment and indoor thermal comfort depending on experts' weighting, responses, and recommendations. The outcomes postulate that the implementation of reflective paints solutions would achieve the highest percentages of whole-building energy savings with 21%, 19%, and 17% for Aswan, Cairo, and Alexandria, respectively, improving indoor thermal comfort levels.

KEYWORDS

building performance simulation, carbon footprint, cost-efficiency, energy efficiency, techno-economic assessment, thermal comfort, thermal insulation

1 | INTRODUCTION

In several nations, the transition to alternative energy infrastructure is being started as fossil fuels are entering their tertiary phases. The most critical issue nowadays would be to handle this transition, minimizing negative effects and combining various technological solutions over time: short-term carbon reduction and sequestration of fossil fuel, implementation of energy-efficient technologies, and alternating to green energy resources.[1,2] Buildings are currently the world's largest electricity consumer, probably accounting for over one-third of global energy consumption.[3] Building end-uses account for about 30%-40% of global energy demand in 2019.[4-6] Most of this energy is being used for heating, ventilation, and air-conditioning (HVAC) systems.[3,7] A building's HVAC system operation, guaranteeing human comfort and maintaining air quality, is vital for energy optimization.[8] Among building end-uses, HVAC systems represent approximately 50%.[4,9,10] Population growth and thermal comfort are the main contributors to the continuing increase in buildings' energy demand. In developing countries, approximately half of the energy in a building is used for space conditioning, with an additional 20% of plug loads, illumination, and other internal processes.[11] Research in developing nations argue that HVAC and lighting consumption can sum up to 77% of the building energy demand.[12,13] In hot regions, HVAC can contribute to about 50%, while lighting can reach more than 35% of the building's aggregate energy use.[9,10,13,14] Buildings' HVAC energy utilization can be affected directly by overestimations leading to systems oversizing.[10,15,16] Sustainable building designs meeting all of our citizens' operating demands are an immense task in this era. Since a substantial portion of a country's energy demand is related to the built environment, productive approaches should be taken to decrease energy consumption while ensuring that human comfort/health and environmental protection expectations are fulfilled.

Many building owners in developing countries have been conditioned to believe that energy efficiency must be more expensive; however, well-designed, energy-efficient buildings can be developed for less cost than traditional ones. For instance, enhancing the envelope to fit the climatic conditions, can significantly reduce the size of the mechanical systems. Energy conservation without lowering comfort levels contributes to improved use of power. It is not about rationing, reductions, or load disposal but simply a process of identifying excess energy areas and implementing steps to minimize usage.[17] There are significant prospects to decrease power utilization while boosting buildings' performance. Energy-efficient designs are substantially different from each other for hot, dry, and humid regions.[17] New constructions are expected to minimize average power demand by 20%-50% by considering appropriate design strategies in building envelopes, HVAC, illumination, appliances, and others (eg, workplace appliances). Substantial savings over 50% of energy demand compared to an existing building can be attained.[18,19] Early design stages contribute significantly to future performance in terms of resource and energy utilization, and this is where the optimization potential can be leveraged most efficiently and at a relatively low cost. Passive building design parameters ought to be designed to decrease building energy demands, increasing building energy efficiency, as well as the efficiency of active components as HVAC systems should be optimized to reduce energy consumption.[18]

1.1 | Literature review

A building envelope has a substantial effect on energy use as well as peak loads. As the insulating properties of the envelope worsen, energy consumption and peak loads rise. This thermal layer should have an efficient barrier for heat transfer through the building structure, which can be accomplished through an adequate choice of insulators.[20] Annual cooling demand for buildings can be substantially decreased in thermally insulated facilities in hot-dry and hot-humid environments.[19] The use of simulation models and the estimation of building loads enables the optimization of envelope properties by changing the configurations of the walls, roof, or glazing in one-parameter increments.[16] A variety of approaches are being established to create energy models simulating a building/plant model for forecasting loads or cost cuts.[12] These models alter widely in extent from a wall to a full building model by simulating temperature-varying spaces.[12]

To enhance building efficiency, a technique known as the "parametric simulation process" should be used. This methodology allows quantifying the impact of the selected variables on the building energy performance through the iterative execution of several simulation batteries. Local and global sensitivity analysis can be carried out.[21] Local studies are focused on the effects produced by each variable around the base case, modifying one parameter while the rest are keeping constant. Global studies are more interested in quantifying the influences of uncertain inputs over the whole input space, so several parameters are modifying at the same time. Numerous studies previously have looked at the selection of passive building factors to reduce energy utilization in buildings under various climatic conditions.

In four different Iranian environmental conditions, Delgarm et al[22] performed an optimization analysis relying on EnergyPlus models, taking the annual illumination and cooling demands as the objective functions, and the design parameters are the orientation of the building, glazing dimensions, and overhang specification. They concluded that the optimization of building design factors could substantially reduce the energy consumption of buildings. Elsafty et al[23] have been researching the saving of energy usage in commercial buildings in Egypt and its environmental effects. Since a significant portion of energy consumption is consumed by Egyptian commercial buildings, HVAC consumption has been examined. Theoretical research was conducted to use insulation to reduce the energy consumption of the HVAC system. The reductions in HVAC power usage helped solve excess power consumption in Egypt during peak periods of the summer days. Assessing the needed calculations using established software, they found that the inclusion of insulation produced savings around 15% of the annual HVAC energy usage, in addition to reducing (7.78×10^{-7}) tons CO_2 emissions per kWh saved. Bolattürk[7] stated in his research that one of the most important energy-saving strategies in buildings is thermal insulation. He postulated that the determination and selection of the insulation thickness is, therefore, the key focus of many engineering investigations. The structures of walls vary by climate. Bricks or concrete bricks are only coated with thin plaster layers in warm climates, while sandwich walls are used in cold climates. In the research, he opts for extruded polystyrene (XPS) board as an insulation material. He concluded that the optimum insulation thickness of the polystyrene board in buildings varies between 3.2 and 3.8 cm.

Evin and Ucar[24] examined the optimal thickness of thermal insulation added to the building envelope of a four-story residential building in four different climatic zones in Turkey. They concluded that the energy cost was decreased dramatically when the roof is insulated with polystyrene relative to the noninsulated roof. Finally, they recommended applying the same methodology to other building types and in different climatic regions. López et al[25] suggest that the addition of thermal insulation to the built exterior facade is one of the upgrading steps of the building envelope. They also refer to the need to adapt the implementation of successful refurbishment strategies to the climatic conditions and to legalize that in the constructive regulations. Finally, they concluded that, with a reasonably low cost, the façade modification achieves energy savings of about 3%. Yilmaz[26] postulated that the heat capacity of the building envelope should be controlled in hot and dry climatic conditions as it plays a vital role in usable energy. He concluded that a dynamic model of heat transfer during the design phase should be evaluated, particularly in regions located in continental environments. In this design phase, it should be taking into account the ability of the building envelope, as a function of its thermal mass, to regulate the entry of the thermal wave into the building. In their research, Ghose et al[27] analyzed the environmental effects of renovated buildings in New Zealand. They revealed that effective HVAC and smaller window-to-wall ratio should be prioritized in large buildings, whereas the option of façade materials with minimal embodied impacts should be prioritized in small buildings. In the end, all the buildings were planned to have undergone deep energy retrofitting steps, leading to a reduction in operational energy usage by at least 60%.

Lstiburek[28] argues that wall assembly should include control approaches for moisture and thermal transfer. He mentioned that one of the most efficient materials combining both approaches for the hot-dry and hot-humid conditions is polyurethane. An-Naggar et al[29] investigated, through DesignBuilder modeling software, the effect of walls and roof insulation (glass wool [GW]) on energy usage and CO_2 reduction in Egyptian residential properties. Almost 40% of the reduction in the energy used by the air conditioning system is obtained once heat insulation is used in external walls and roofs, reflecting a substantial decrease in energy bills. Al-Saadi et al[30] studied the energy performance of a residential house in Oman (hot climate). They concluded that adding polystyrene insulation to walls and roofs contributed to about 18% annual energy savings. Radwan et al[15] explored the influence of construction materials on buildings' energy consumption. They concluded that 8% of energy reduction in hot-humid climates may be achieved through building construction materials. Sala et al[31] investigated the building performance employing insulating envelopes. They recommended an overall heat transfer coefficient (U-value) of the exterior building facades and roofs (0.32 W/m^2 K for external walls and 0.26 W/m^2 K for the roof) as low as possible to reduce energy losses and the summer overheating on exposed surfaces (southern, western, and eastern exposure).

Aditya et al[32] reviewed the various insulating materials that relate to buildings. They classified the insulating materials' heat exchange properties into two categories, (1) mass insulation category, which are materials that can slow the heat transfer by conduction and (2) reflective insulations reflect radiation heat due to a low emittance reflective surface, preventing transfer from one side to another. Moujaes and Brickman[33] studied the effect of reflective paints on energy usage in US residential buildings in hot arid climates. Their research resulted in 11% energy reductions when reflective paint is applied to the building roof only. Zhang et al,[34] stated in their study that applying high reflectivity materials coatings building external walls proved to be an effective way to reduce heat gains from solar radiation and reduces energy needs. They concluded that building exterior walls with reflective coatings can reduce about 15% of energy. Raimundo et al[35] aimed at identifying the most energy-efficient and cost-effective thermal insulation options in five buildings in Portugal's region. They concluded that expanded polystyrene insulation is the most cost-effective thermal insulation material, and its ideal location is in the midsection of the building envelope. Verichev et al[36] applied an energy simulation in Chile to determine the thermal transmittance of exterior walls for single-family buildings and the energetically optimum thickness of thermal insulation. They argue that by designing the house with a mind on energy efficiency, the carbon emissions may be decreased by 20%. According to Zilberberg et al,[37] structural engineers typically disregard energy performance. They ensured, using models, that adding insulation resulted in a substantial reduction in operating energy usage while minimizing the relative impact of noninsulated thermal mass in the building envelope in hot semi-arid climates. Anh and Pásztory[38] analyzed numerous thermal insulation materials that have been produced in recent years and declared that they have proven their usefulness in buildings due to benefits such as low density, high thermal resistance, and cost-effectiveness.

1.2 | Research gap and aims

Previous studies show that energy conservation is critical research that legislators are carrying out in their efforts; however, it is overlooked in many developing countries. To the authors' understanding, this literature shows a research gap investigating building energy conservation in different hot climate zones (as those of Egypt). When an energy conservation approach argues that installing insulation reduces energy usage, operational costs, and ecological effects, the resulting indoor thermal comfort response should be considered in the decision-making process. Finding a comprehensive approach that considers the different aspects of energy efficiency is a way to assist project decision-makers through their designs and retrofits. Even though there is a simulation tool that evaluates multiple sustainability aspects, decision-makers find it difficult when considering widely different aspects. This study presents these aspects in various forms of quantitative measures for various insulating materials. It also demonstrates how it could be implemented through an enviro-economic evaluation and the resulting thermal comfort, evaluated through Fanger Predicted Mean Vote (PMV) and Discomfort hours (DCH) , on an existing institutional building in three different American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) climatic zones in Egypt.

With Egypt's vision 2030, the authors aim to address this gap, with this article, by presenting a method that integrates various parameters affecting energy efficiency into the decision-making phase for the appropriate efficient design option for the facility owners and policy-makers. The use of this methodology based on parametric analyzes that consider different cost functions (demands, cost, and comfort), allows creating a decision-making matrix that helps when developing energy efficiency policies and normative in existing buildings that need renovation.

2 | THEORETICAL ANALYSIS

The management of various dynamic interactions, illustrated in Figure 1, to achieve reliable buildings and system solutions that meet the future requires an integrated and comprehensive subsystem approach.

Building energy models (BEM) primarily use physical methods to predict building efficiency, building energy use, evaluate building designs, inspect code compliance, and assess buildings based on standard-established rating requirements, among other potential applications before construction.[39,40] The energy consumption of buildings is the result of a plethora of different end-uses. Therefore, it may become difficult for BEM to consider the thermal response of the building demands and to anticipate the operational and functional characteristics of the systems that react to these needs. Besides, HVAC simulations in building prototypes typically provide energy utilization outputs that allow the optimization of the building performance.

To evaluate the energy performance of the whole building, HVAC units, or the characterization of the building envelope, simulation tools are used. The sequence of analyses carried out by a building modeling tool is fully described by Ayres and Stamper.[41] This modeling approach is broadly endorsed and implemented nowadays in global simulation tools,[42-45] for example, ESP-r, BLAST, TRNSYS, DesignBuilder, and EnergyPlus, which have the

FIGURE 1 Building's subsystems dynamic interactions

opportunity to handle building dynamics effectively. Based on precise physical properties of buildings vacancy schedule, geographic environments, nature of construction, and weather conditions, these tools estimate total energy utilization as well as the energy used by HVAC, operational scheduling, illumination, etc.[46-49] Nevertheless, the existence of certain accurate data is challenging and, in some situations, is difficult to collect, leading to different sources of uncertainties that influence the final results of the building performance.

A variety of commercial building benchmark simulations have been established by the US Department of Energy (DOE) providing a standardized framework for BEM.[50] A typical BES model is formulated employing "first principles of building physics" and is considered a reliable model.[51]

In this research, the dynamic simulation program, DesignBuilder, has been used to model the energy performance of buildings. This simulation tool considers specified internal heat gains, air exchange between zones, air exchange with the outside environment, and convective heat transfer from the zone surface to estimate the heat balance in each thermal zone through the use of an Integrate Simulation Manager that combines the surface heat balance and air heat balance. This integrated simulation solution solves simultaneously building system and plant configurations. The heat balance method is an iterative computation approach that requires the simultaneous solution of a set of equations for each hour of the day for the zone air and each of the external and interior surfaces, considering internal and external ambient conditions as well as physical properties of the construction layer.[52,53]

The use of this simulation tool allows the dynamic calculation of the energy balance, linking the energy consumption of the building and the air conditioning load with the climatic conditions and the thermal inertia of the building envelope.

3 | METHODOLOGY

The energy performance of an institutional building in Cairo (Egypt) has been evaluated using the dynamic simulation tool DesignBuilder. This software is able to analyze the energy quantification of the selected retrofitting behavior, analyzing the impact of the measure on the thermal loads of the building. Considering the climatic conditions for three representative cities in Egypt, as well as the current building's construction and operational data, a baseline model based on on-site measured consumption is validated using ASHRAE validation measures. Grounded on the annual thermal loads' outcomes of the validated baseline model, a local sensitivity analysis was performed to identify which factors are more sensitive to annual energy and peak design loads.[21] Accordingly, to this study, the installation of thermal insulation in façades and roofs, conventional and radiative insulators, has been advocated. With this aim, a series of simulations were conducted, considering the building needs as well as the normative constraints. The retrofitting parameter is modified from the original values in each simulation, while the rest remained unchanged. The series of tests were chosen based on data from retrofit products available on the Egyptian market.

The multiapproach decision-making in this study highlights the most influential insulation in comparison with the annual loads of the baseline, through a full techno-economic assessment as well as the environmental impact (CO_2) taking into consideration the resulting indoor thermal comfort, correlated with each insulation material, as a priority expressed in Fanger PMV and the number of DCH. The graphical methodology applied is illustrated in Figure 2.

4 | CLIMATE DATA

The most recent cooling degree days data for some Egyptian cities are summarized in Table 1.[54,55] Typical climate conditions are prescribed for locations where most stations are subject to long-term hourly observations.[56] Building codes are usually related to representative climates within an enforcement jurisdiction. These climatic conditions are obtained as averages from local to regional databases based on 30 years of measurements.[57] The guidelines for these codes are set up by national regulations and regional or international standards. This last category highlights the standards established by the DOE and the ASHRAE. In collaboration with the DOE, ASHRAE, based on surface measurements, has developed climate zone maps used by several building codes.[57]

The climate in Egypt is considered semi-desert with hot dry summers, moderate winters, and very little rainfall. According to the Köppen Geiger classification, two climate zones have been identified for Egypt[58,59]: BWh and BSh. Regions classified as BWh correspond to hot desert climates, while regions classified as BSh correspond to hot semi-arid climates. Nevertheless, the ASHRAE classification[56] divides Egypt into three climatic zones: very hot-dry (1B), hot-dry (2B), and hot-humid (2A). A representative city of each climate zone has been selected: Aswan, Cairo, and Alexandria. Table 1 shows the latest recommended annual design conditions based on 0.4% and average wind speed[56] for the three selected locations describing, besides, the annual Direct Normal Irradiation.[60]

5 | BUILDING MODEL

The base case of this research represents a building located in Cairo, Egypt. To develop the model of this base case, all the necessary information feeding the model is gathered: geometry, envelope characteristics, internal gains, and building zones. The validity of the model is checked from comparisons between the obtained outputs of the model and the experimental measurements registered in the real building placed in Cairo. Finally, the influence of the building uses has been analyzed highlighting the importance of the envelope characteristics.

5.1 | Site location

The building is located in the New Administrative Capital, Cairo, Egypt, as shown in Figure 7. New Cairo capital city is located 35 km east of Cairo. The new capital is developed with the strategic vision for a smart city integrating its smart infrastructure to provide many services

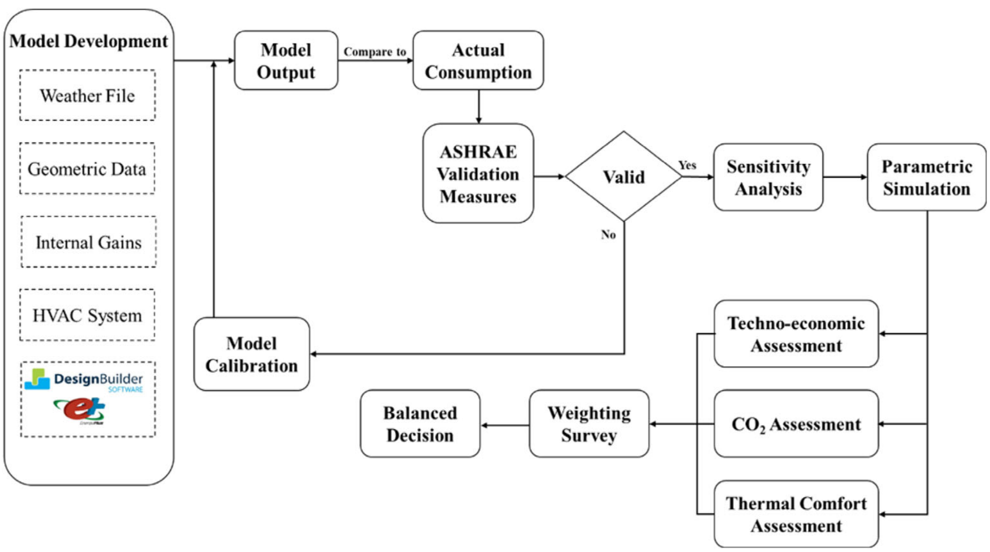

FIGURE 2 Graphical methodology

to citizens. The facility consists of approximately 11 350 m^2, as shown in Figure 3.

5.2 | Envelope specifications

For the case study, the as-built data were collected from the facility management office. The wall area is 3473 m^2, while the roof area is about 1913 m^2. The building envelope components have almost the same values used in most nonresidential buildings in the Egyptian market[9,10] and are listed in Table 2.

5.3 | Internal gains

Internal gains are simply the internal loads generated inside the building, including occupancy, ventilation rates, lighting, equipment, and schedules.

Occupancy density and ventilation requirements

Occupant density and ventilation rates by space type were defined according to *ASHRAE Standard 62.1-2016*.[61]

TABLE 2 Building envelope data

Exterior walls	
U-factor (W/m^2 °C)	1.924
Roof	
U-factor (W/m^2 °C)	2.27
Window	
Average window fraction (window-to-wall ratio)	30%
Glass-type	6 mm double blue glass/ 6 mm air gap
U-factor (W/m^2 °C)	3.094
SHGC	0.503

TABLE 1 Design conditions for three different locations[54-56]

Location	Cooling degree days	ASHRAE climate zone	Dry-bulb temperature (°C)	Wet-bulb temperature (°C)	Direct normal irradiation (kWh/m^2)	Wind speed (m/s)
Aswan	6564.1	1B	44.1	21.1	2254	4.04
Cairo	4861.7	2B	38.2	21.2	2036	3.58
Alexandria	3739.9	2A	33.2	22.4	1955	3.92

FIGURE 3 The building, the model, and the site location via Google Maps

Lighting and plug loads

Lighting loads are set according to *ASHRAE Standard 90.1-2016* using the space by space method.[62] The energy used by appliances that are regularly wired into a socket, commonly involving office and other miscellaneous equipment, computers, and others that are hard to estimate is widely known as plug loads. These values were also set according to *ASHRAE Standard 90.1-2016*.[62]

Operating schedules

The building is operating 5 days per week from 8 AM to 4:30 PM. As with most educational facilities, in August institutional buildings are operating with about 50% capacity due to the annual vacations.

5.4 | Building zones

The building consists of 13 different occupied zones as tabulated in Table 3.

5.5 | Model validation

For the model to be effective, it should be capable of predicting the dynamics of the system and taking into consideration the relevant factors affecting the system. To build energy models that contribute to a sustainable energy future, the validity of the simulations should be guaranteed so that the findings of the simulations can be trusted. With this aim, the built-up model was validated with two different approaches which are recommended by the National Renewable Energy Laboratory.[63] The annual Energy Use Intensity (EUI in kWh/m^2) obtained with the simulation model has been compared with other institutional buildings located in hot climates and referenced in the literature, as illustrated in Figure 4. The comparative study is a useful technique because it does not require data from a real building, and it also highlights if further investigation is needed. Due to the absence of a model of reality, the comparative approach is most effective when used with other validation techniques.

In validation tests, BEM are linked to measured data from existing buildings. Based on that, the second approach is validating the model EUI compared to the field site measurements extracted from the Building Management System. The validation data were graphed in Figure 5. To exhibit the representativeness of the simulation model based on the variability of the measured data, two indices have been calculated, as recommended by the ASHRAE guideline 14:2015[68]: Coefficient of variation of the root mean square error (CVRMSE) and normalized mean bias error (NMBE). According to this guide, the value must be less than ±10% for the NMBE coefficient and less than 30% for the CVRMSE coefficient. For the calibrated model, the estimated NMBE is 6%, while the CVRMSE is about 3%.

TABLE 3 Building occupied zones

Zone	Area (m^2)	Area %
Call center	43	0.5
Classrooms	693	7.9
Corridors	2253	25.8
Dry lab	407	4.7
GYM	150	1.7
Lecture halls	707	8.1
Libraries	466	5.3
Lobby	827	9.5
Lounges	453	5.2
Meeting rooms	276	3.2
Offices	1584	18.2
Receptions	634	7.3
Restaurants	237	2.7
Total	8728	100

5.6 | Building energy use

In building energy analytics, sensitivity analysis plays a vital role. From both energy simulations and empirical analysis, it can be used to identify the key variables influencing building thermal performance. Analyzing the building energy use, approximately, HVAC systems

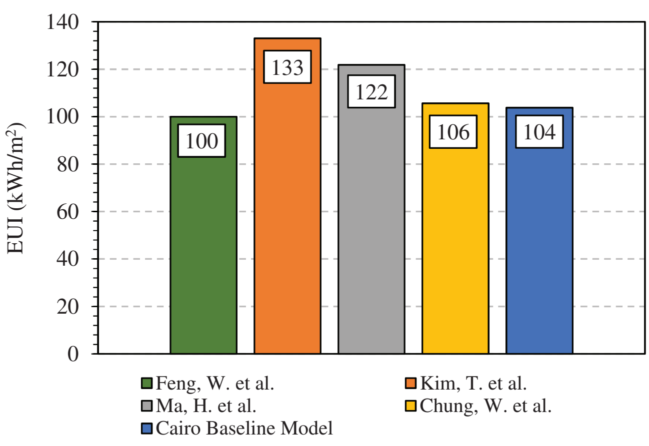

FIGURE 4 Cairo Baseline Model EUI compared to different studies[64-67]

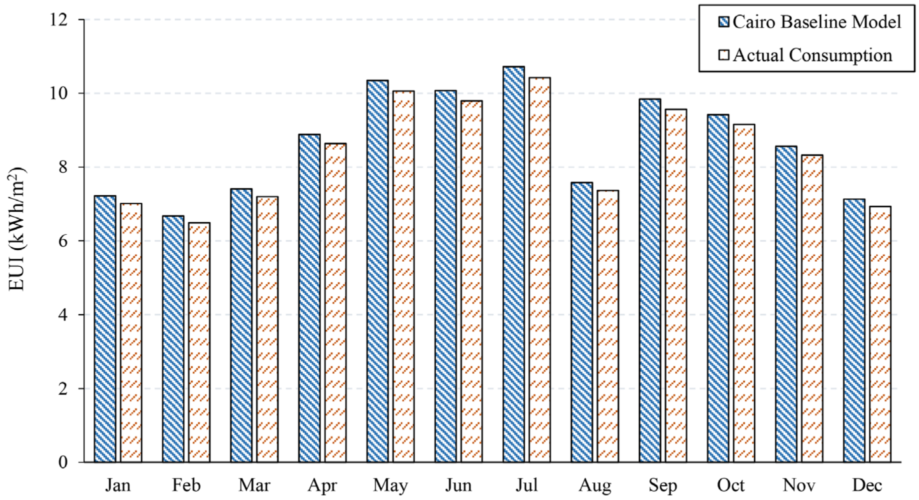

FIGURE 5 Cairo baseline model validation—Cairo, Egypt

compromise half the building energy use, which aligns with.[9,10,13,17,67] A sensitivity analysis was undergone for the validated baseline model to quantify the portion of each parameter affecting the building energy usage, as illustrated in Figure 6. This differential sensitivity analysis shows that the most influential variables in the total heat gain are the walls and the roof, reaching a percentage of approximately 40%. Based on this result, this study aims to investigate the effectiveness of different types of insulating materials and thicknesses in different hot climatic zones of Egypt.

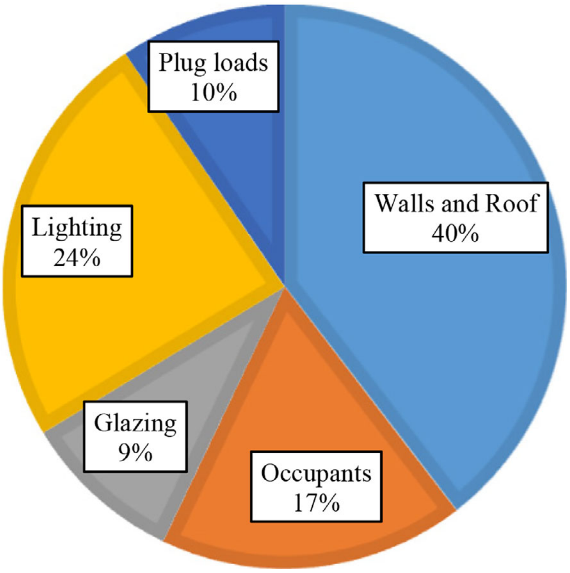

FIGURE 6 Cairo baseline model sensitivity analysis

5.7 | Insulation in buildings

In Egypt, the thermal performance of the building envelope is quite important in the morning and late afternoon, when a significant amount of solar radiation is occurring. The thickness of the insulation material can be determined depending on the building's annual cooling/heating energy requirements. Since Egypt has a wide geographic location and numerous climatic regions, it has been divided by ASHRAE into three climate zones. Some Egyptian governates, such as the South Region and the Mediterranean coastal governates, differ among very hot dry, hot dry, and hot humid climates with a longer cooling season than the heating season.

In terms of the energy economy, ensuring efficient thermal insulation in regions where the cooling demands in buildings are predominant in contrast to the heating requirements is quite necessary. In these regions, more studies focusing on indoor comfort related to the implementation of insulation must take place in parallel with the development of a country's energy economy.

This study analyzes the behavior of a building in different climatic zones, modeled with the same architectural and physical characteristics except for the insulating material and its thickness. The materials under investigation are conventional in the Egyptian market such as XPS, polyurethane (PU), GW, and imported material such as reflective paint (RP). The available thickness for the three insulating materials is 25, 50, 75, and 100 mm, respectively.

6 | RESULTS AND DISCUSSION

The outcomes of the proposed retrofits are analyzed and discussed in order to evaluate the building performance annually. With this aim, an enviro-economic assessment is carried out to address the energy and carbon footprint reductions and the resulting thermal comfort according to the implementation.

6.1 | Building energy performance

This section evaluates the building response to the implementation of different insulation materials as well as different thicknesses for the three proposed cities. The results obtained by the simulation batteries are tabulated in Table 4.

The results revealed that in different Egyptian regions, the building performance differs. For areas with warmer climatic conditions (Aswan: zone 1B), the energy requirements are higher. As expected, greater insulation thicknesses achieve greater energy savings, but this progression follows a logarithmic profile as shown in Figure 7. The highest percentages of energy savings are achieved with the reflective paint material (21%, 19%, and 17% for Aswan, Cairo, and Alexandria, respectively) followed in descending order by XPS (maximum savings of 17% for Aswan, 10% for Cairo, and 6% for Alexandria), GW (maximum savings of 17% for Aswan, 10% for Cairo, and 6% for Alexandria), and polyurethane (maximum savings of 16% for Aswan, 9% for Cairo, and 5% for Alexandria).

6.2 | Carbon footprint assessment

Reducing energy utilization minimizes carbon footprint and deterioration of the environment. The EPA[69] has reported that 0.0007 CO_2 tons are produced by 1 kWh of consumer electricity. Relative to the baseline model, Table 5 indicates the reduction percentage of CO_2 emissions in the three locations when different insulation thicknesses are considered. The higher the insulation thickness, the higher the reductions achieved in the CO_2 emissions. The best environmental material tested is reflective paint followed by XPS, GW, and polyurethane.

6.3 | Techno-economic assessment

Techno-economic analysis is a cost-benefit assessment based on multiple approaches. These evaluations are used for tasks including:

- Assess the economic viability of a given project
- Investigate lifetime cash balances (eg, investments)
- Assess the possibility of various levels and implementations of technology
- Compare the economic efficiency of various technological solutions offering a similar function.

The cost assessment is discussed in this section, defining the terminology used and indicating the assessment methods. Four indicators have been evaluated: internal rate of return (IRR), return on investment (ROI), net present value (NPV), and payback period (PBP).[10,70] The indicator IRR is used in the economic analysis to measure the profit margins of potential investments. The indicator ROI is defined as the ratio to measure the benefit of the investment of capital. In the present, money is worth more than the same amount in the future due to the time value of money. The difference between both the present value of cash inflows and the present

TABLE 4 6.1. Building energy performance (BEP) due to insulation

	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
Model	EUI (kWh/m^2)		
Baseline	115.55	103.77	96.09
25 mm PU	101.51	96.33	91.89
25 mm XPS	100.59	95.41	91.10
25 mm GW	101.23	95.78	91.29
50 mm PU	98.71	94.93	91.53
50 mm XPS	97.91	94.23	90.63
50 mm GW	98.46	94.56	90.80
75 mm PU	97.39	94.20	91.24
75 mm XPS	96.58	93.66	90.51
75 mm GW	97.07	93.83	90.57
100 mm PU	96.76	94.10	91.18
100 mm XPS	95.80	93.29	90.47
100 mm GW	96.26	93.46	90.41
RP	91.73	83.59	79.78

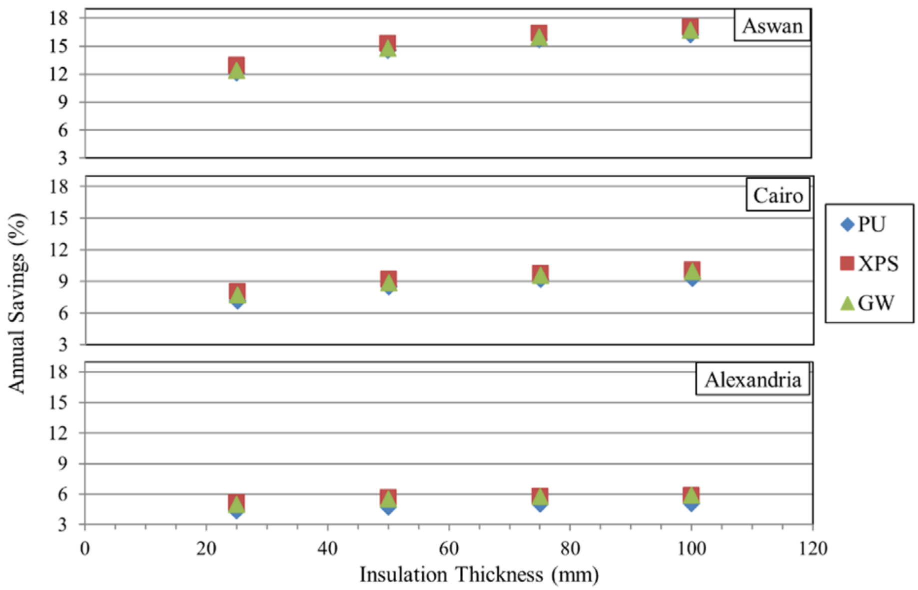

FIGURE 7 Annual energy savings based on the insulation thickness for the three studied cities

TABLE 5 Carbon dioxide reduction percentage

Model	Aswan, Egypt	Cairo, Egypt	Alexandria, Egypt
	CO_2 reduction %		
25 mm PU	12.15	7.17	4.37
25 mm XPS	12.94	8.06	5.19
25 mm GW	12.39	7.70	5.00
50 mm PU	14.57	8.52	4.75
50 mm XPS	15.26	9.19	5.68
50 mm GW	14.79	8.87	5.51
75 mm PU	15.71	9.22	5.04
75 mm XPS	16.42	9.74	5.81
75 mm GW	16.00	9.58	5.75
100 mm PU	16.26	9.31	5.11
100 mm XPS	17.09	10.10	5.85
100 mm GW	16.69	9.93	5.91
RP	20.62	19.45	16.98

value of cash outflows is the indicator NPV. A positive NPV indicates that the proposed earnings generated by the investment surpass the anticipated costs. Finally, the PBP indicator is the time before the cash inflows repay the initial investment. The examination takes into account the most recent electricity prices of 1.6 Egyptian pounds (EGP) per kWh in Egypt for commercial buildings. The investment in this study is the increased cost between the baseline model and the proposed models with a constant discount rate of 10% among all models. The insulation costs according to the latest Egyptian market prices and the economic assessment outcomes are summarized in Table 6. The full economic analysis is introduced in the Appendix Table A1.

Despite the environmental impact of increasing the insulation thickness, Table 6 reflects that the addition of 25 mm of XPS tends to be the most cost-efficient insulation among the conventional insulations studied for Egypt. On the other hand, a tremendous IRR indicator is shown with the implementation of the RP insulators to the building envelope.

6.4 | Insulation and thermal comfort

If facility managers can all agree on one aspect, it is that resident comfort concerns are their most common regular operational challenge. Thermal comfort is defined by

ASHRAE as the "condition of mind that expresses satisfaction with the thermal environment."[71] This is a subjective concept in which an individual may feel hot while another may feel cold nearby, being able to invert these arguments the next day. Even a new facility may struggle to keep most citizens satisfied the majority of the time. Although comfort is a highly personal experience for each individual, numerous standards highlight the optimum values for maintaining indoor ranges. Unfortunately, effective techniques in developing countries are rarely used in practice, perhaps because this information is not well accepted or recognized.

An obvious advantage of keeping residents more comfortable is that it will reduce complaints and, as a result, operating and maintenance expenses. Thermal comfort, when delivered intelligently and meaningfully, reduces the operational energy bills. Furthermore, buildings' thermal comfort and energy consumption are associated with design decisions during various design stages.[69] Therefore, with a priority on thermal comfort, environmental indoor quality, and the resources required to condition residents and facilities, designers should be founded to serve as a liaison between both the health and building sciences.

Heat storage and release are influenced by the material itself, thickness of the material (x), as well as other factors such as thermal conductivity (k) and specific heat capacity (C_p), which are natural thermophysical properties of the material.[72,73] To simplify the interaction between these parameters, the relationship between the insulation implementation (whether different material or thickness) and thermal comfort should be illustrated as well as the whole-building energy performance. Investigating and solving these puzzle components in a comprehensive framework almost often result in a better, more effective approach at a reasonable cost. This section examines the influence of building insulation's impact on thermal comfort using the Fanger methodology. To evaluate thermal comfort, Fanger created a 7-point scale standardized later by both ANSI/ASHRAE 55[71] and ISO 7730.[74] The PMV scale is often used to represent the comfort level scaled as follows: (+3 hot, +2 warm, +1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, and −3 cold). In addition to thermal sensation, DCH analysis used in the study is an assessment based on whether the temperature and the moisture content indoors are within the ASHRAE thermal comfort range or not. Fanger PMV in parallel with DCH analysis is investigated. Figure 8 relates the resulting PMV to the insulation implementation, while Figure 9 illustrates the DCH related to the different simulated insulation materials for the three locations.

Figure 8 illustrates the Fanger PMV outcomes for the three locations under investigation. In baseline models, the highest values of PMV are reached in Aswan, Cairo, and Alexandria, respectively. According to the dynamic simulations' outcomes, an improvement in indoor comfort can be easily noted. The simulations reveal that building envelopes retrofits in the three locations—almost efficiently—limit the human sensation between −0.5 (slightly cool) and +0.5 (slightly hot) most of the operating times.

Figure 9 relates the different insulating materials under investigation to DCHs and the percentage of their

TABLE 6 Techno-economic assessment outcomes

		Aswan, Egypt		Cairo, Egypt		Alexandria, Egypt	
Model	**EGP/m²**	**IRR**	**PBP (years)**	**IRR**	**PBP (years)**	**IRR**	**PBP (years)**
25 mm PU	115	41.51%	2.2	19.12%	4.2	5.56%	7.5
50 mm PU	200	27.27%	3.2	9.67%	6.1	−2.96%	11.9
75 mm PU	283	18.90%	4.2	4.03%	8	−7.47%	15.9
100 mm PU	358	13.65%	5.2	−0.15%	10.1	−10.62%	19.9
25 mm XPS	63	81.55%	1.1	45.27%	2.1	25.12%	3.4
50 mm XPS	103	59.18%	1.6	30.63%	2.9	13.98%	5.1
75 mm XPS	140	46.36%	2	22.33%	3.8	7.36%	6.8
100 mm XPS	165	40.69%	2.3	18.86%	4.3	4.19%	8
25 mm GW	71	69.79%	1.3	38.20%	2.4	20.53%	4
50 mm GW	119	49.45%	1.9	24.58%	3.5	9.85%	6.1
75 mm GW	165	37.85%	2.4	17.21%	4.5	3.85%	8.1
100 mm GW	201	31.71%	2.8	13.04%	5.3	0.63%	9.7
RP	56	145.30%	0.6	123.36%	0.8	100.01%	0.9

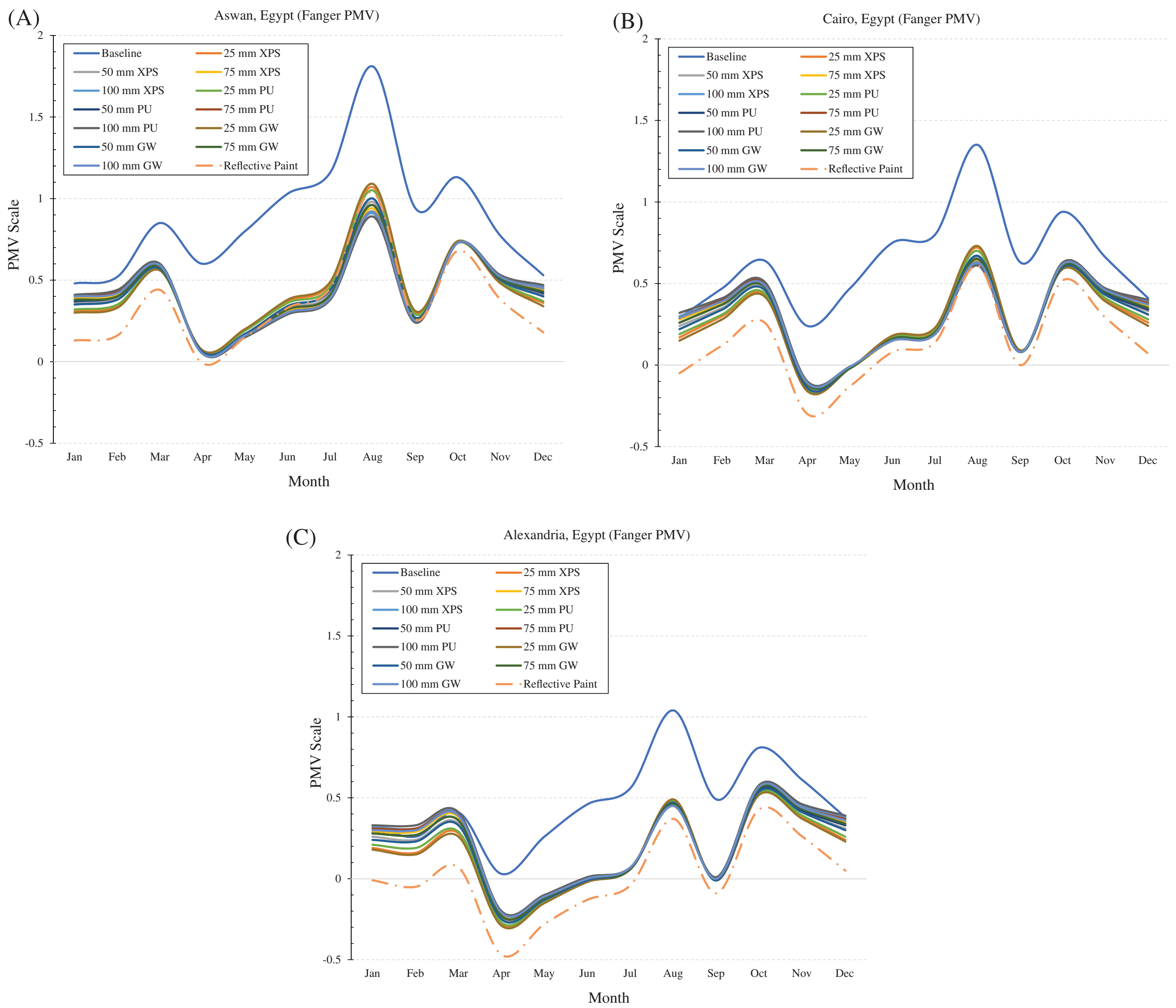

FIGURE 8 Resulting PMV of different insulations, (A) Aswan, (B) Cairo, and (C) Alexandria

reduction. It highlights the importance of thermal insulation in reducing the resulting indoor discomfort. Besides the enviro-economic revenues, a percentage of discomfort hours reductions is notable due to the implementation. The study reveals that 100 mm PU reduces discomfort hours by about 30%. However, according to the balanced decision approach, PU is excluded due to its enviro-economic performance. Among the conventional insulations, a balanced decision would be the 25 mm XPS for both the enviro-economic and thermal comfort performance. Oppositely, the imported reflective paints thermal performance in Aswan is derived by the higher solar radiations in the location followed by Cairo and Alexandria. Due to its tremendous economic revenue, reflective paints should be imported and implemented in Egyptian buildings.

6.5 | Weighted decision

The decision-maker in a construction process should evaluate the efficiency of various energy-efficient solutions in terms of sustainability, making the multidecision approach a useful tool for evaluating the whole system. Along with its high ability to weigh multiple alternatives with different factors for the selection of an appropriate solution, the multiapproach decision represents a reliable technique for analyzing difficult challenges.

Two methods have been proposed to the weighting of sustainability evaluation criteria: (1) equalize the weights of the parameters and (2) give particular weight to each parameter.[75] This study undergoes a weighting technique to accurately improve the whole-building performance. The weighting methodology in this study has used three cost functions: (1) economic assessment, (2) environmental impact, and (3) thermal comfort. Building owners, experts, and consultants' opinions are surveyed upon the weighting percentage of each of the three cost functions. The survey resulted in 45% for thermal comfort, 35% for economic revenue, and 20% for environmental impact. Accordingly, the weighting methodology is implemented, and the outcomes are graphically illustrated in Figure 10 below.

7 | CONCLUSION

The multidecision approach proposed in this study is a mindset about sustainability all in all, instead of one factor such as energy consumption. A local sensitivity analysis has been carried out to evaluate the influence of the insulating materials on the building's energy, thermal comfort, and performance of a previously validated

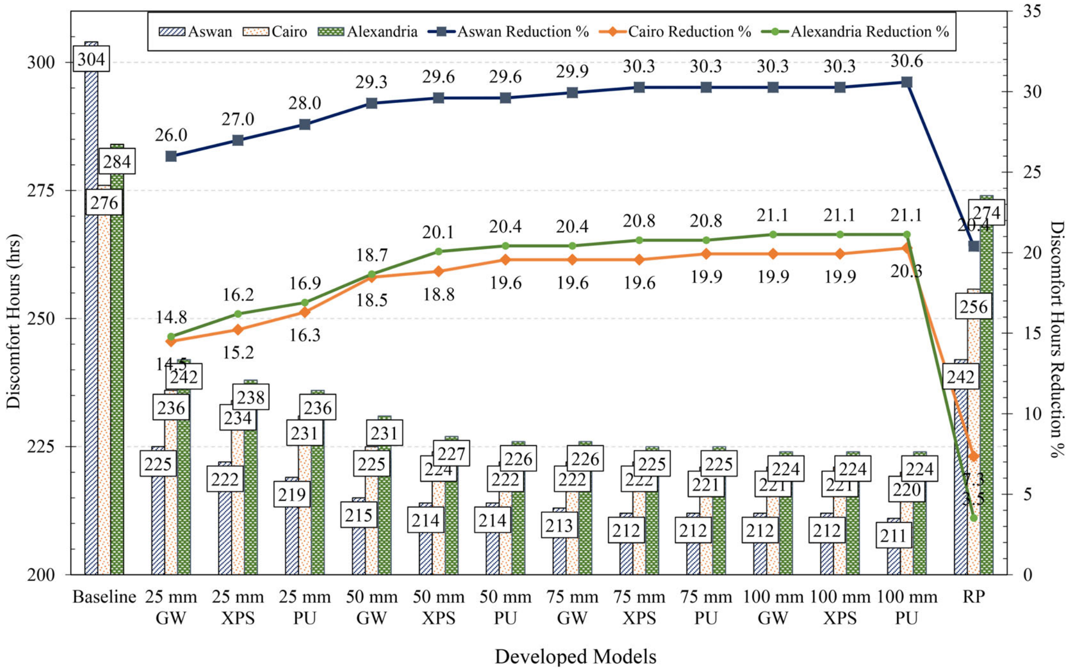

FIGURE 9 Discomfort hours and reduction percentage related to insulation type

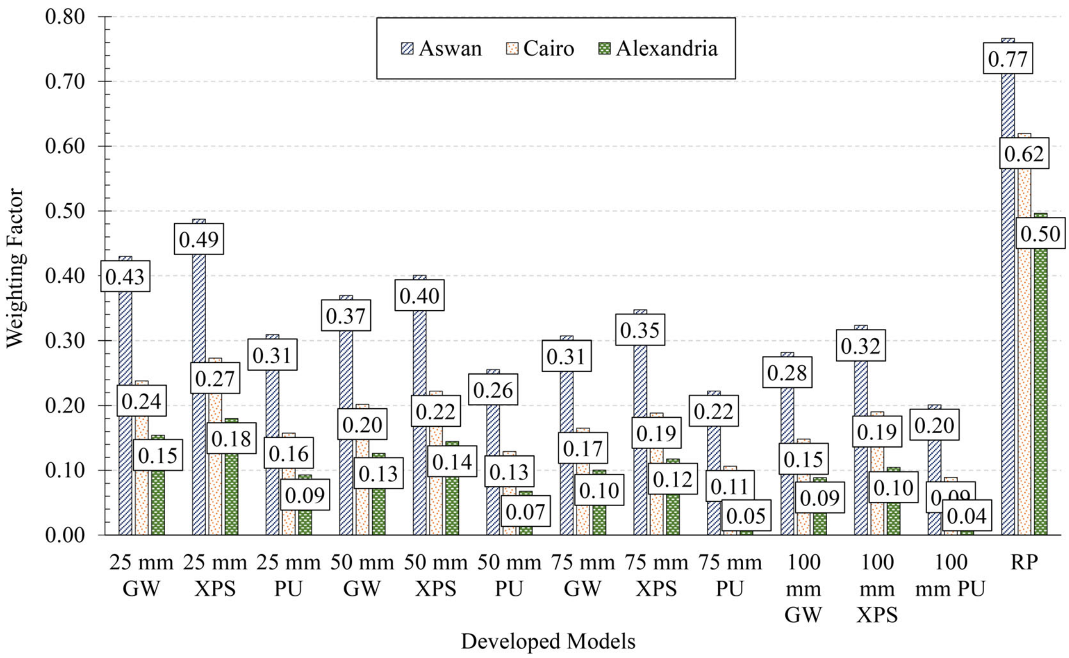

FIGURE 10 Weighted decision matrix outcomes

institutional building in three different ASHRAE climate zones. This approach enables decision-makers to choose the most appropriate design options based on a balanced decision policy.

Concerning uninsulated buildings, the study outcomes can be outlined as:

1. The best energy and environmental response are obtained for the reflective paint material followed by XPS, GW, and polyurethane.
2. Among conventional insulating materials, the XPS with 25 mm of thickness tends to be a cost-effective investment with the highest IRR, ROI, NPV, and the least PBP.
3. Nonetheless, thermal comfort should be given priority in the retrofit decision. Although reflective paints tend to be the best enviro-economic solution, the implementation of conventional insulations would reduce the DCH compared to baseline and reflective paints models in hot climates.
4. Reflective paints show the greatest enviro-economic benefits with energy savings of 21%, 19%, and 17% in parallel with a decrease in DCH of about 20%, 7.5%, and 3.5%, respectively, for Aswan, Cairo, and Alexandria.
5. Depending on the weights of different parameters, a balanced decision would be the reflective paints.

The local authorities in developing nations should consider enforcing energy standards to set energy efficiency minimum standards for newly developed buildings and to retrofit present buildings, ultimately contributing to reduced energy use, carbon dioxide emissions, and human discomfort hours.

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APPENDIX A

TABLE A1 Table represents the full economic analysis calculations

		Aswan, Egypt				Cairo, Egypt				Alexandria, Egypt			
Model	EGP/m^2	IRR	ROI	NPV (EGP)	PBP (years)	IRR	ROI	NPV (EGP)	PBP (years)	IRR	ROI	NPV (EGP)	PBP (years)
25 mm PU	115	41.51%	27.15%	1 062 393	2.2	19.12%	14.38%	271 514	4.2	5.56%	8.13%	−116 103	7.5
50 mm PU	200	27.27%	18.78%	942 969	3.2	9.67%	9.85%	−15 662	6.1	−2.96%	5.09%	527 367	11.9
75 mm PU	283	18.90%	14.27%	651 058	4.2	4.03%	7.52%	−377 475	8	−7.47%	3.81%	943 366	15.9
100 mm PU	358	13.65%	11.67%	322 579	5.2	−0.15%	6.01%	−770 100	10.1	−10.62%	3.05%	1 339 990	19.9
25 mm XPS	63	81.55%	52.72%	1 452 071	1.1	45.27%	29.47%	661 780	2.1	25.12%	17.58%	257 591	3.4
50 mm XPS	103	59.18%	38.24%	1 560 322	1.6	30.63%	20.69%	590 497	2.9	13.98%	11.83%	101 295	5.1
75 mm XPS	140	46.36%	30.15%	1 518 986	2	22.33%	16.07%	457 508	3.8	7.36%	8.86%	−85 666	6.8
100 mm XPS	165	40.69%	26.65%	1 478 102	2.3	18.86%	14.15%	368 154	4.3	4.19%	7.59%	−214 294	8
25 mm GW	71	69.79%	45.07%	1 334 618	1.3	38.20%	25.15%	576 458	2.4	20.53%	15.11%	194 565	4
50 mm GW	119	49.45%	32.08%	1 409 298	1.9	24.58%	17.28%	464 863	3.5	9.85%	9.93%	−4241	6.1
75 mm GW	165	37.85%	24.94%	1 326 297	2.4	17.21%	13.41%	303 074	4.5	3.85%	7.45%	−226 218	8.1
100 mm GW	201	31.71%	21.31%	1 226 820	2.8	13.04%	11.39%	150 513	5.3	0.63%	6.27%	−404 113	9.7
RP	56	145.30%	94.63%	2 552 339	0.6	123.36%	80.17%	2 116 179	0.8	100.01%	64.81%	1 652 930	0.9

Abbreviations: GW, glass-wool; NPV, net present value; PBP, payback period; PU, polyurethane; ROI, return on investment; RP, reflective paint; XPS, extruded polystyrene.

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Evaluating heating, ventilation, and air-conditioning systems toward minimizing the airborne transmission risk of Mucormycosis and COVID-19 infections in built environment

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ABSTRACT

This ongoing global pandemic of the COVID-19 has generated a significant international concern for our respiratory health. For instance, the breakout of the COVID-19 pandemic was directly linked to the spread of infectious particles in indoor environments between humans, underlining the significance of rigorous and effective actions to limit the transmission of diseases. Recently, Mucormycosis infections in COVID-19 patients have been identified. This investigation aims to investigate potential infection control HVAC solutions for indoor environments, as well as their core mechanisms for reducing infectious disease risk through simulation models of a valid building in a hot climatic region. Considering recent international recommendations, the investigation relies on a methodology of testing a validated building energy model to several systems in the light of infectious diseases prevention. All proposed models are exposed to cost analysis in line with carbon emissions, and indoor thermal conditions. The analysis outlined through parametric simulations, the effectiveness of the proposed DOAS in supplying 100% fresh ventilation air and enhancing the control of the indoor relative humidity simultaneously. Finally, through an enviro-economic assessment, the study concluded that the DOAS model reduced the CO_2 emissions to 691 tons, with a potential of reducing HVAC and whole-building energy use by 37% and 16%, respectively in the hot arid climate, with a return on investment of about 6%.

1. Introduction

With infections of the COVID-19 virus being recorded all across the world, health authorities are concentrating their efforts on limiting the virus's transmission. Filter masks do not provide complete protection against coronaviruses, and protection should be based on the employment of many measures simultaneously [1,2]. Therefore, understanding how coronavirus transmits allows us to take the essential precautions to avoid infections. The virus that causes COVID-19, according to specialists, transmits primarily through person-to-person contact. Respiratory diseases could be spread by aerosols of varying sizes: respiratory droplets are greater than 5–10

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BES	Building Energy Simulations
CAV	Constant Air Volume
CO_2	Carbon Dioxide
CVRMSE	Coefficient of Variation of the Root Mean Square Error
DBT	Dry Bulb Temperature
DOAS	Dedicated Outdoor Air System
FCU	Fan Coil Units
GWh	Gigawatt Hours
HVAC	Heating, Ventilation, and Air Conditioning
LPD	Lighting Power Densities
NACA	National Asthma Council Australia
NMBE	Normalized Mean Bias Error
PBP	Payback Period
ROI	Return on Investment
VAV	Variable Air Volume
WBT	Wet Bulb Temperature

μm in diameter, while droplet nuclei are less than 5 μm in diameter [3]. According to existing information, the COVID-19 virus is largely spread between humans via respiratory droplets and interactions [4–8]. When a human comes in physical contact (within 1 m) with a patient who has respiratory symptoms (e.g., coughing or sneezing), his or her mucosae (mouth and nose) or conjunctiva (eyes) are at risk of exposure to possibly infectious respiratory aerosols. Fomites in the immediate area of the infected person can potentially transmit the disease [9]. Therefore, COVID-19 viral infection can emerge through direct touch with infected people as well as indirect contact with surfaces in the nearby area or items touched by the infected individual. Airborne spread differs from droplet transmission in that it relates to the occurrence of microorganisms within droplet nuclei. They are commonly regarded to be less than 5 μm in diameter particles that can exist in the air for extended durations, around 3 h, and be transferred to someone else across distances wider than the traditional 1–2 m [10]. The generation of aerosols, as well as the wide range of virus loads in patients, necessitates tailoring the HVAC systems' safety to the unique control requirements. Indoor transmission of SARS-Cov-1 and MERS-CoV was thought to be aided by HVAC systems that were not intended to accommodate infectious people [11].

Along with the COVID-19 pandemic, regions in India have begun announcing a "black fungus" epidemic as incidences of the deadly rare infection increase among COVID-19 patients. Mucormycosis is a fungal infection that has a 50% death rate. It affects patients leading to the nose, blurry vision, pain in the chest, blood coughing and breathing difficulties [12]. The fungus can eventually travel to the brain necessitating significant surgical operations to remove the eye or a portion of the skull and jaws. COVID-19 could have played a role in vulnerability to Mucormycosis [13]. Mucormycosis is transmitted by coming in touch with fungus particles in the environment. After the fungus reaches the skin through a scratch, burn, or other sorts of skin damage, a skin infection can develop [14]. Mucormycosis has no vaccination till now but there may be some treatments to reduce the odds of acquiring mucormycosis for patients with weak immunological systems [14]. Additionally, inhaling spores from the air could cause the infection to spread to the lungs or sinuses. Daily, the average human breaths in around 16 kg of air [15]. Inhaling contaminated air may include especially aggressive compounds, is a major cause of sickness leading to the common cold and flu, bronchitis, headache, eye inflammation cough, dizziness, and the development of toxins in the blood [15]. Since the fungi that cause mucormycosis are so abundant in the surroundings and atmosphere, it is impossible to escape inhaling fungal spores. Fungi are common in indoor spaces and cause a variety of medical conditions, from local non-invasive pathologies to aggressive and widespread infections [16]. According to Ref. [16], there are currently no techniques or equipment available to totally eradicate the fungus from indoor facilities. Mold contamination is unavoidable; however, the use of air filtration systems, isolation, and environmental protection measures can help to reduce occupants' exposure [16]. Whether it is a chilly, rainy season or a hot, humid summertime, indoor activities could cause moisture and the growth of molds. Mold can spread on a variety of surfaces, including walls, clothing, books, toys, and even CDs. It has the ability to convert beloved treasures into musty antiques.

In general, for black mold to expand and thrive, it requires a source of moisture. Molds form spores that are transmitted through the air. These spores can be found indoors in any environment. They cannot be avoided, and they can survive in environments where mold cannot thrive. Mold spores grow in moist conditions. It is necessary to enhance the methods now available for studying indoor fungus in clean surroundings, as well as to identify markers of indoor air quality indoors [16]. Airborne mycological examinations should provide information regarding indoor environmental quality and thus should be performed regularly in indoor facilities [16]. Numerous studies have suggested increasing the amount of outdoor air considering outside air can be used to decrease any indoor airborne contamination. In some regions, a huge quantity of outdoor air might cause moisture control issues. A case report provided by Russo et al. [17] advocates employing a multidiscipline strategy to drive stakeholder responsibility of the environment and enhance Infection Prevention (IP) procedures. They added that the upcoming difficulties, include maintaining a constant focus on recognized risks and handling practices transition when new objectives and issues emerge. In hot climatic regions, William et al. [18,19]

investigated the effectiveness of the dedicated outdoor air system (DOAS) on a healthcare facility's energy consumption. On the other hand, and with the global concerns about mucormycosis, it is brought to our attention that HVAC systems can effectively enhance the control of moisture indoors, eliminating the growth of mold.

With the increasing concern about health issues and airborne transmission, several references limited the humidity levels to certain conditions [20,21]. Dietz et al. [20] recommended, according to ASHRAE, 40–60% indoor relative humidity to assist in minimizing the virus spread and survival. However, the virus survival in aerosols was determined at a relative humidity of 65% [20]. Furthermore, according to NACA, relative humidity of 30%–60% is quite suitable for most occupants [22]. Low humidity leads to very dry air, which enhances the probability of airborne diseases such as flu, probably as they survive longer in cool dry environments and also because of irritable nasal passages that facilitate their capture. Eczema could be inflamed, and dry skin could also be painful [22]. Dust mites and mold, which are two of the most prevalent, irritating asthma and allergy triggers, thrive in higher humidity environments [22,23]. Fig. 1 introduces the ideal humidity levels viruses, respiratory irritations, and mold growth.

Bearing this in mind, the study in hand proposes and highlights the effectiveness of implementing an energy-efficient temperature and humidity independent control system, DOAS, in buildings for today and future pandemic preventions through various simulations on a valid building.

2. Methodology

A dynamic simulation model is employed to analyze the thermal performance of a facility in Cairo, Egypt. In this investigation, the modeling tool DesignBuilder, featuring the EnergyPlus user interface, has been used. Designers can assess the retrofitting behavior using simulations, examining the influence of the action on the building's thermal loads. The baseline model is validated based on actual metered consumption confirmed by ASHRAE validation techniques, considering the weather conditions of Cairo, Egypt, as well as the existing facility's construction and operating records. Following the validation, different HVAC systems are investigated for enhanced indoor environmental quality with the aim to reduce indoor contamination and mold prevention (Fig. 2).

3. Model development and validation

To ensure comfort conditions, a particular quantity of energy must be supplied or extracted (heating/cooling) from the building space. This energy is heavily influenced by exterior climatic conditions including outdoor air temperature, humidity levels, and wind characteristics, as well as internal occupancy, heat and moist flow through the envelope and interiors, etc. [25]. This energy serves as a load on the HVAC system installed to control the building's heat and moisture. Cairo is classified as a hot climate region with annual design conditions of DBT and WBT given by 38.1 °C and 21.2 °C respectively [26]. The HVAC system serving the baseline model is terminal FCU. The recommended ventilation rates and occupant densities are based on the room type as per ASHRAE standard 62.1 [27]. Internal loads, including LPD and plug loads, are according to ASHRAE [26,28].

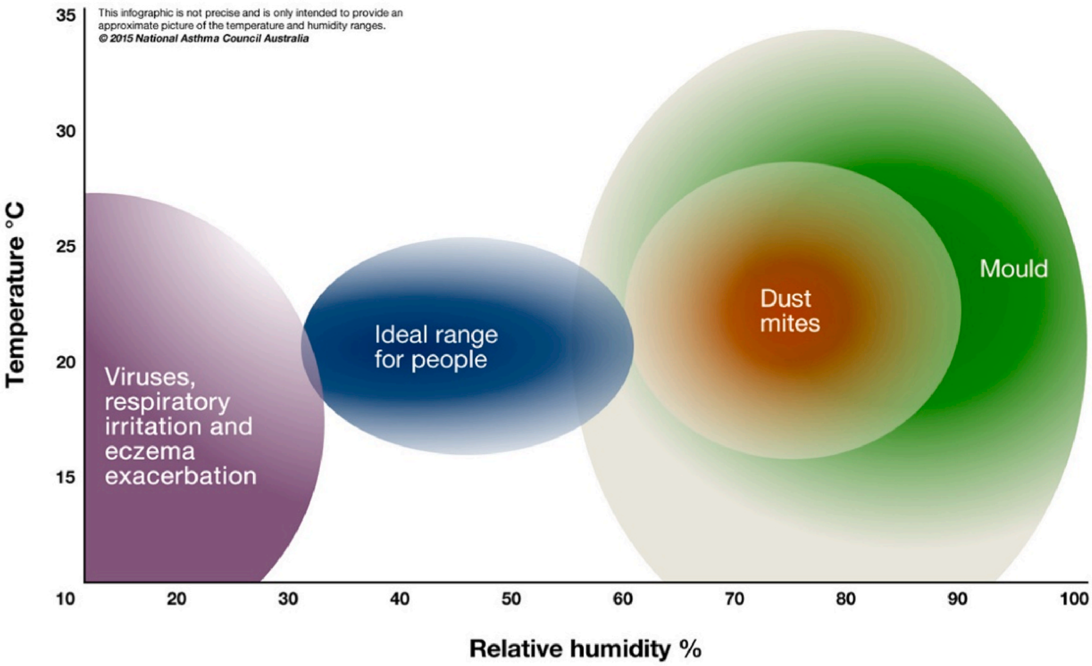

Fig. 1. Ideal temperature and humidity levels for respiratory problems patients [24].

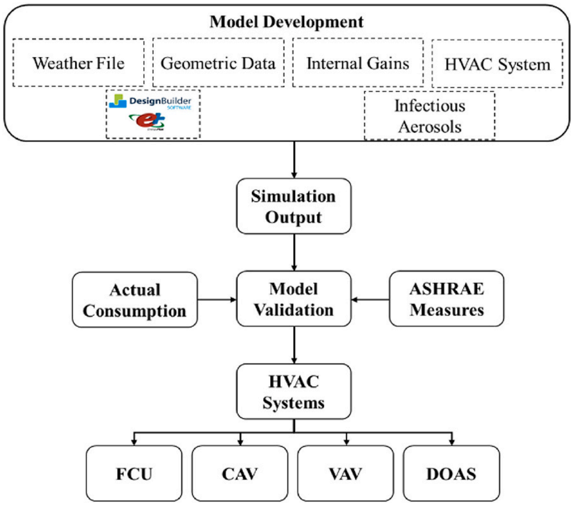

Fig. 2. Modeling flowchart.

Fig. 3 shows the model layout and Table 1 summarizes the building description.

Table 2 tabulates the occupied building zones percentage.

The forward approach in developing a BES model is predicting the outcome variables using the model's precise structure and parameters in response to a specified set of inputs variables [25]. White-Box models are those that have been generated using this approach. Since most of the energy transfer mechanisms are integrated into the formation of the BES modeling structure, those simulations are quite reliable [25]. The building model is validated compared to the on-site metered energy data. As shown in Fig. 4, the model tends to be realistic and comparable to the existing building with a CVRMSE of about 3% and an NMBE of 6%.

Following the validation, a sensitivity analysis is undertaken to reveal that around 45% of the building energy use goes to the HVAC systems aligned with the values provided by Refs. [18,19,25,29,30].

4. HVAC systems

The prime purpose of the HVAC system is to keep the temperature and humidity level of the building space within the appropriate limit levels while taking into consideration air velocity, quality, and noises. HVAC systems are classified into various classifications according to the conditioned air delivery method. This manuscript classified the HVAC systems under investigation into terminal units as FCU, All-Air systems as CAV, VAV, and hybrid system DOAS.

FCU is equipment that draws airflow from a room into the unit and then blows it across a cooling or heating coil. They typically only circulate indoor air, requiring a secondary ventilation system and being inefficient compared to typical solutions as variable air volumes.

In high-occupancy buildings, recirculating ventilation systems through one or more typical air handling units, CAV and VAV, condition a mixture of outside and recirculated air (supply air) to more than one ventilation zone [26]. These zones could have different outside air fractions, as specified by ASHRAE, but every air handling unit just provides one fraction [26]. Therefore, the air handler's outdoor airflow rate is determined by the zone requiring the highest outdoor air fraction [26]. Consequently, all other zones obtain extra outside air than required, known as over ventilation.

In many HVAC applications, the cooling and dehumidification system is unable to properly meet the imposed load requirements of the building when the dehumidification load is high, either due to large internal moisture generation or high ventilation flow rate [31]. Consequently, the improper design and operation of the HVAC equipment to address humidity control issues can lead to poor indoor air quality, and excess energy use [31].

The DOAS system is a conceivable alternative HVAC solution supplying the exact amount of recommended outside ventilation air required by each zone [19]. The air is introduced at lower dew-point temperatures, allowing it to absorb the space latent load as well as a portion of the sensible load, effectively decoupling the latent and sensible loads [18,19,32].

The four HVAC systems under investigation line diagrams are illustrated in Fig. 5.

5. Results and discussion

Proper ventilation and indoor air quality have been proven, in previous studies, to reduce the indoor contaminants and virus spread through airborne transmission. The study in hand has some limitations. This analysis is based on testing the systems on institutional buildings, assuming proper ASHRAE ventilation requirements are set, the building operates during working hours in the hot climate. Future work should include the investigation of these systems on different building types, e.g., healthcare facilities, commercial, and

Fig. 3. Model isometric.

Table 1
Building summary.

Location	Cairo, Egypt
Climate	Hot-Arid
Use	Institutional
Stories	6
Built-up Area (m^2)	11,350
Conditioned Area (m^2)	8728
Walls U-Value (W/m^2. K)	1.924
Roof U-Value (W/m^2. K)	2.27
Window-Wall Ratio	30%
Glazing U-Value (W/m^2. K)	3.094
Glazing SHGC	0.503

Table 2
Building zones percentage.

Zone	Area (m^2)	Area %
Call Center	43	0.5
Classrooms	693	7.9
Corridors	2253	25.8
Dry Lab	407	4.7
GYM	150	1.7
Lecture Halls	707	8.1
Libraries	466	5.3
Lobby	827	9.5
Lounges	453	5.2
Meeting Rooms	276	3.2
Offices	1584	18.2
Receptions	634	7.3
Restaurants	237	2.7
Total	8728	100

worship buildings.

Similar to the idea of Chirico and Rulli [33] in examining the problem of thermal conditions indoors, and to effectively introduce an efficient design for hot climatic regions, the HVAC systems for a validated building is tested and the annual overall building response is addressed through a reliable dynamic building simulation tool.

Temperature and humidity are known to enhance viral transmission if not well controlled [33]. Most HVAC system operates on controlling the indoor environment based on indoor temperature control. The simulations show that all systems are approximately resulting in the same indoor temperature control as graphically illustrated in Fig. 6a. However, according to several studies mentioned earlier, the influential factor for virus survival is moisture and relative humidity. With this in mind, the simulated models are tested against humidity levels control. According to the simulations, the FCUs are the poorest in controlling indoor relative humidity. The CAV and VAV systems have almost the same indoor environmental quality as they just differ in the operating conditions. The CAV changes the supply temperature with a constant airflow to handle the indoor loads, while the VAV systems supply a constant temperature with a variable air flow rate which affects the energy positively. According to the DOAS operating principle, the simulations

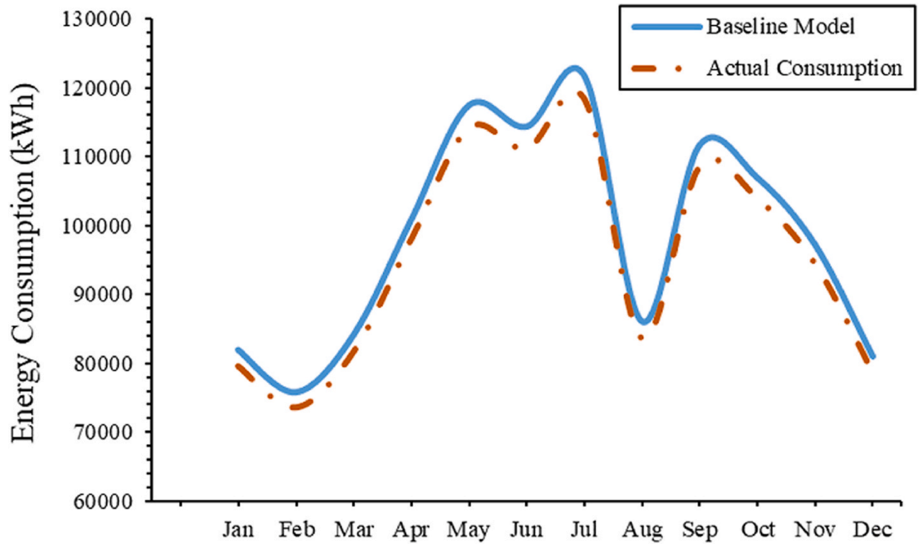

Fig. 4. Model validation.

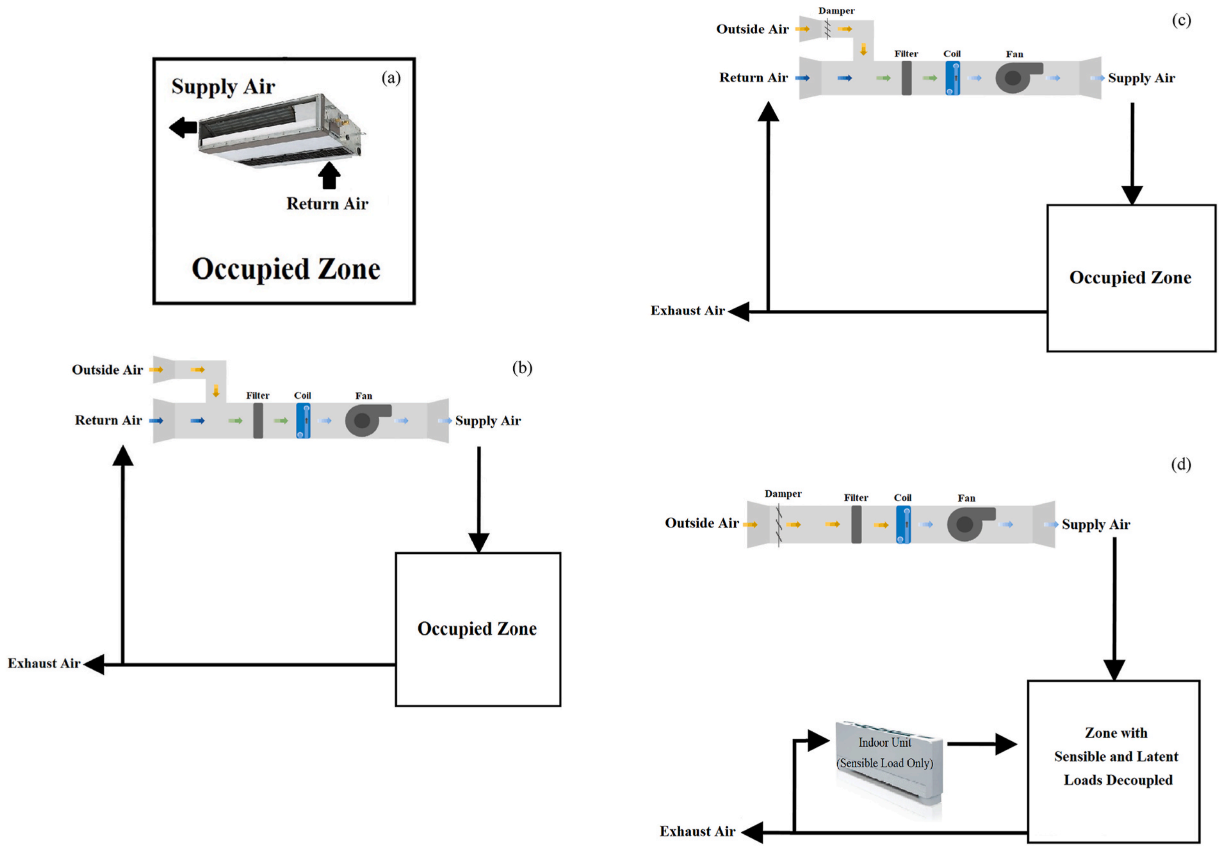

Fig. 5. Tested HVAC Systems, a) FCU, b) CAV, c) VAV, d) DOAS.

revealed the effective temperature and humidity independent control of the proposed DOAS. Fig. 6 illustrates a) temperature and b) relative humidity for the tested models investigated.

The models are also tested for the resulting whole-building energy use, HVAC energy utilization, and CO_2 emissions. The outcomes are graphically illustrated in Fig. 7.

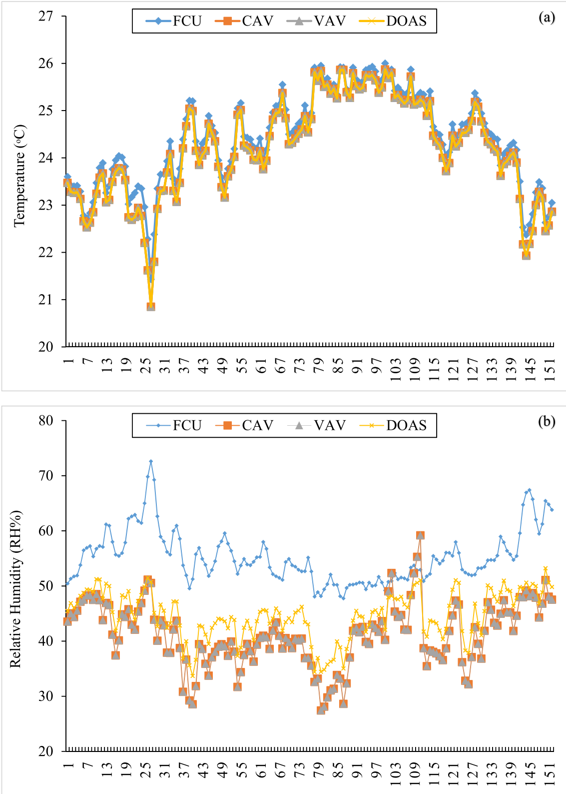

Fig. 6. Models Comparison: a) Temperature and b) Relative Humidity.

As Fig. 7 shows, DOAS is significantly reducing the HVAC energy consumption, as well as the whole building energy use. As with any engineering project, the proposed models are to undergo a cost analysis before implementation. Following the cost assessment procedures by Ref. [34], Table 3 shows the cost analysis results of each implementation according to the surveyed prices in Egypt[1] and compared to the baseline model. The investment in this study is the cost difference between the proposed system and the baseline FCU model. The running cost and savings are calculated based on 1.6 EGP per kWh, the latest tariff [35,36].

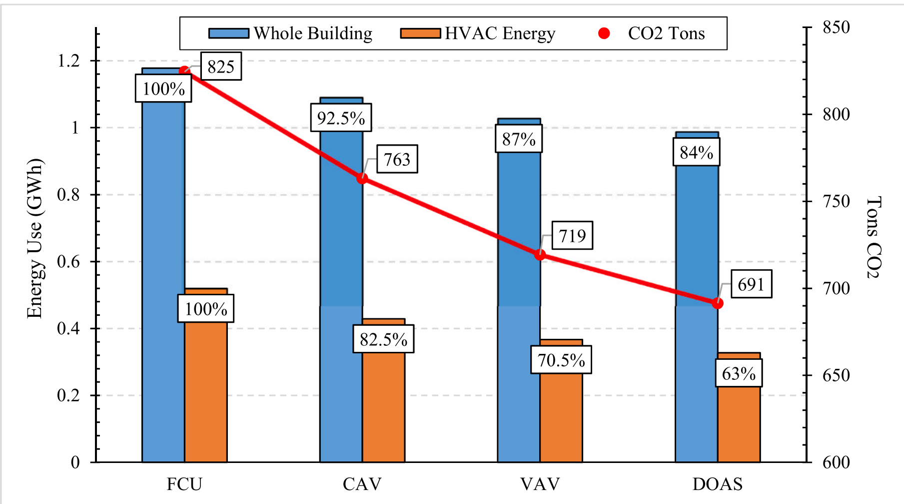

Fig. 7. Models energy responses and CO_2 reductions.

[1] Based on Egyptian market prices, 2021.

Table 3
Proposed models cost analysis.

Model	Whole Building Energy Use (GWh)	HVAC Energy Use (GWh)	HVAC Initial Cost (USD)	Building Running Cost (USD)	Total Savings	ROI
FCU	1.17	0.52	483,674	119,724	–	–
CAV	1.09	0.43	845,578	110,823	8,900	1.62%
VAV	1.03	0.37	1,011,017	104,444	15,279	1.91%
DOAS	0.99	0.33	703,517	100,402	19,321	5.80%

Despite the cost-effective potential of the DOAS shown in Table 3, the current situation of the global epidemic necessitates prioritizing systems that provide higher levels of outdoor air. The proposed DOAS has proven its ability to energy-efficiently support the building with the recommended ventilation rates. It additionally shows a great potential toward indoor humidity control with noticeable enviro-economic potential compared to other HVAC systems.

Authorship contributions

Conception and design of study: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.
Acquisition of data: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.
Analysis and/or interpretation of data: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.
Drafting the manuscript: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.
Revising the manuscript critically for important intellectual content: Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.
Approval of the version of the manuscript to be published (the names of all authors must be listed):
Micheal A. William, María José Suárez-López, Silvia Soutullo, Ahmed A. Hanafy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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